Measuring the Top Quark Mass

Adam Gibson

UC Berkeley Qualifying Exam

November 21, 2003

- Why measure the top mass?
- What we've done so far – Run I style CDF measurement
- What I'm working on now – D0-style matrix element method
- Prospects for D0-style method at CDF, including work on transfer functions

Standard Model

- SM so far very successful
  - Predicted W, Z masses
  - Compatible with a huge array of experimental data
- SM consistency checked to high precision
- A few loose ends tied up in last ten years
  - Top quark, ν_τ
- Ongoing exploration
  - Nature of ν's
  - CKM matrix and CP violation
  - H boson still not observed
- Tevatron unlikely to discover H with only 4 fb^{-1}
- Top a fundamental particle
  - Yukawa coupling a fundamental parameter of SM

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2			Quarks spin = 1/2		
Flavor	Mass GeV/c^2	Electric charge	Flavor	Approx. Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0	u up	0.003	2/3
e electron	0.000511	−1	d down	0.006	−1/3
ν_μ muon neutrino	<0.0002	0	c charm	1.3	2/3
μ muon	0.106	−1	s strange	0.1	−1/3
ν_τ tau neutrino	<0.02	0	t top	175	2/3
τ tau	1.7771	−1	b bottom	4.3	−1/3

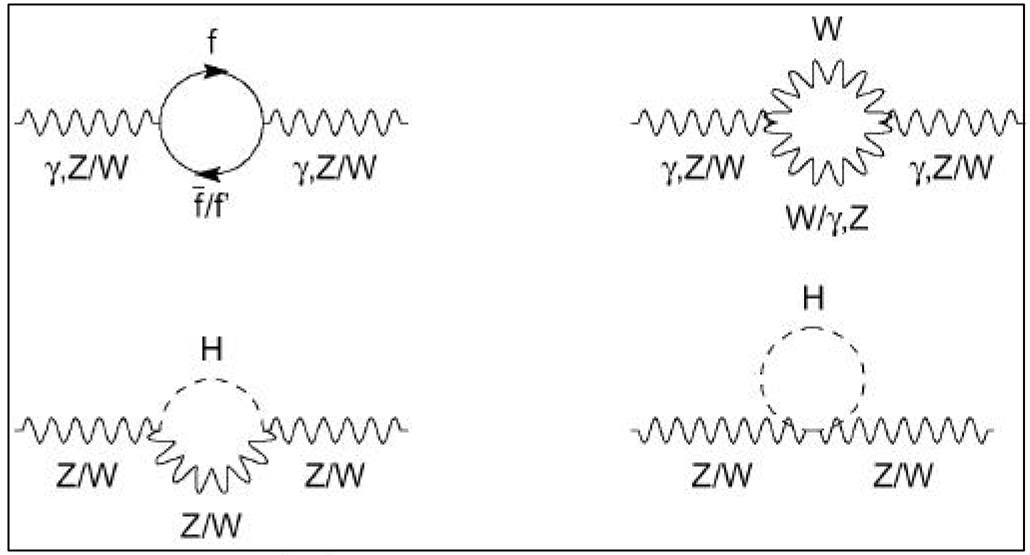
BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0
EW (EWSB) spin = 0		
H	?	0

Radiative Corrections

Fermions affect couplings



$$G_{\mathrm{F}} = \frac{\pi\alpha}{\sqrt{2}m_{\mathrm{W}}^2 \sin^2\theta_{\mathrm{W}}} \frac{1}{(1-\Delta r)}$$

$$\Delta r = \Delta\alpha + \Delta r_{\mathrm{w}}$$

$$\alpha(s) = \frac{\alpha(0)}{1-\Delta\alpha(s)} = \frac{\alpha(0)}{1-\Delta\alpha_{lept}(s)-\Delta\alpha_{top}(s)-\Delta\alpha_{had}^{(5)}(s)}$$

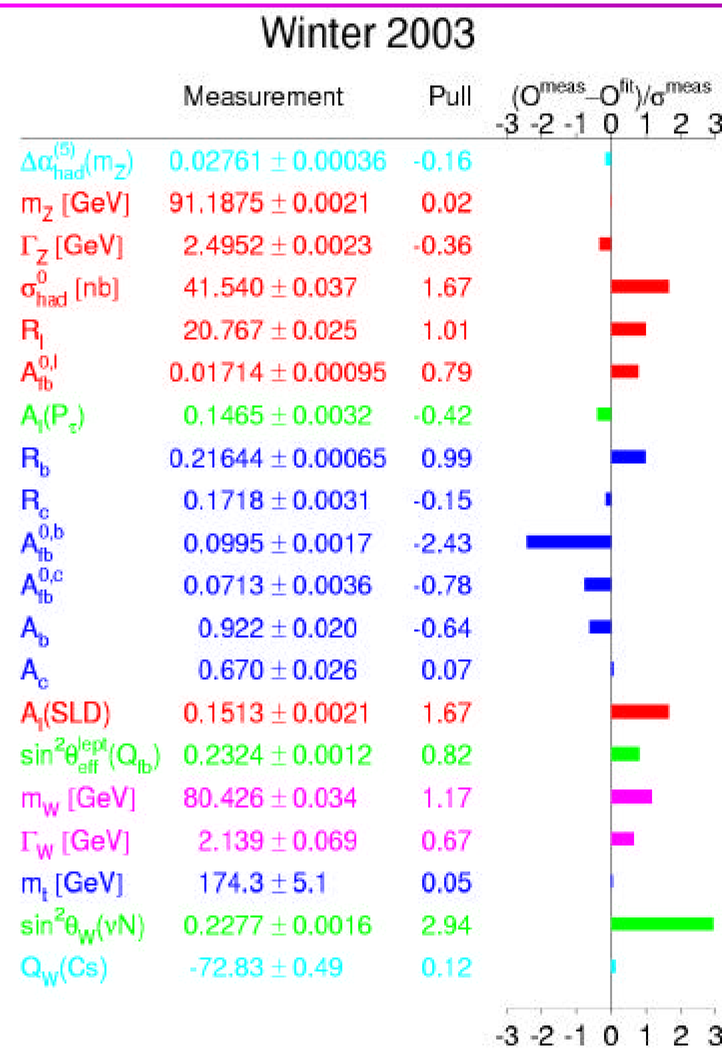
$$\Delta r^{\mathrm{t}} = -\frac{3G_{\mathrm{F}}m_{\mathrm{W}}^2}{8\sqrt{2}\pi^2}\frac{\boxed{m_{\mathrm{t}}^2}}{m_{\mathrm{W}}^2}\frac{\cos^2\theta_{\mathrm{W}}}{\sin^2\theta_{\mathrm{W}}} + \cdots$$

$$\Delta r^{\mathrm{H}} = \frac{11}{3}\frac{G_{\mathrm{F}}m_{\mathrm{W}}^2}{8\sqrt{2}\pi^2}\left(\boxed{\ln\frac{m_{\mathrm{H}}^2}{m_{\mathrm{W}}^2}} - \frac{5}{6}\right) + \cdots$$

P. Renton hep-ph/0206231

Precision Electroweak

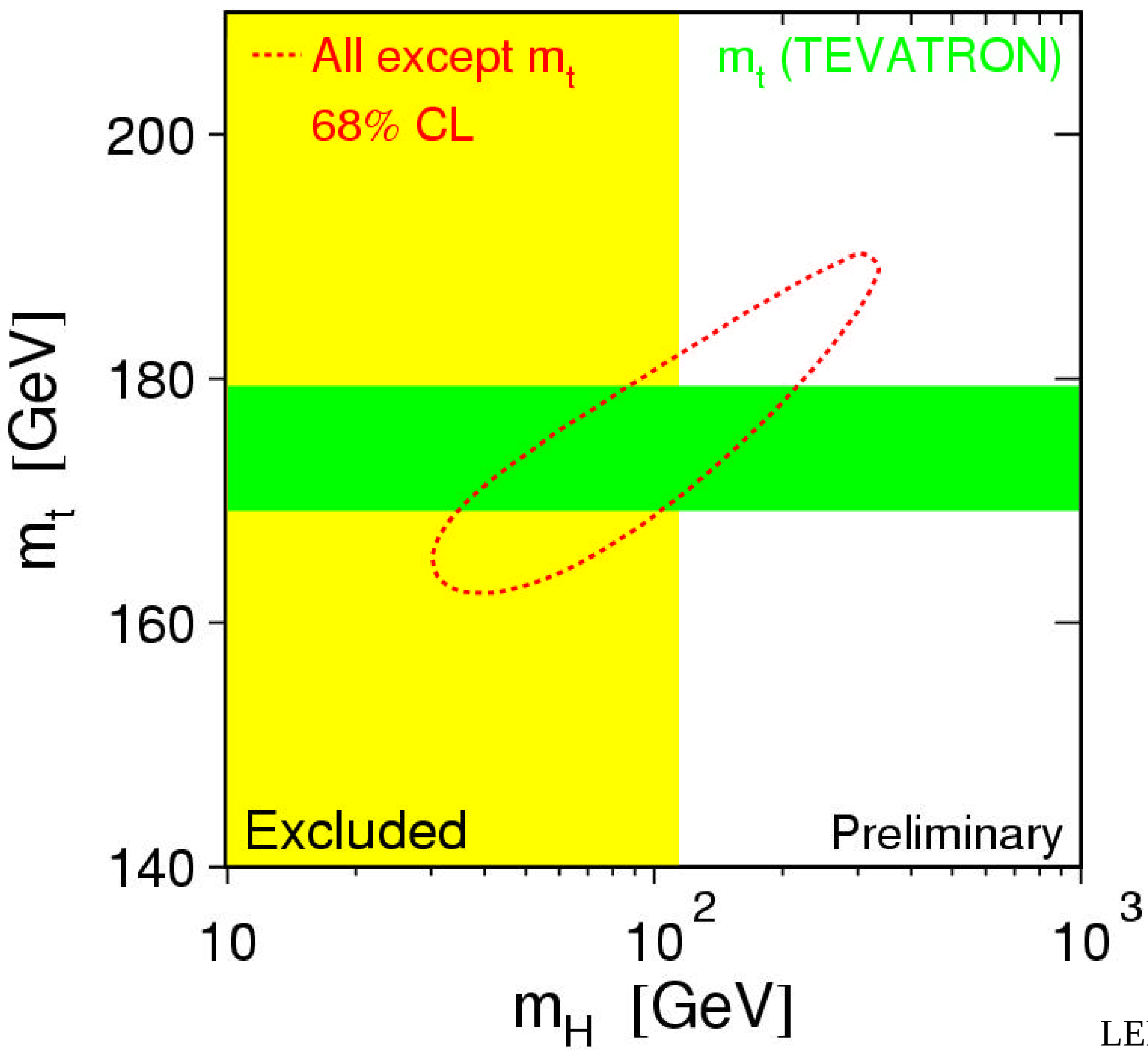
- High-precision measurements of EW observables
  - LEP I, SLD
  - LEP II, SLD w/ polarized beams
  - Tevatron
  - νN scattering (NuTeV)
  - Atomic Physics
- Can “predict” top mass
  - ’94 data at least consistent with first m_t measurement
  - Today LEP plus LEP II 180^{+13}_{-11} GeV
  - Today all Z pole 171^{+11}_{-9} GeV
  - Today global fit $174.0^{+4.5}_{-4.4}$ GeV
- Can predict H mass
  - 96^{+60}_{-38} GeV, <219 GeV 95% CL



LEPEWWG/2003-01

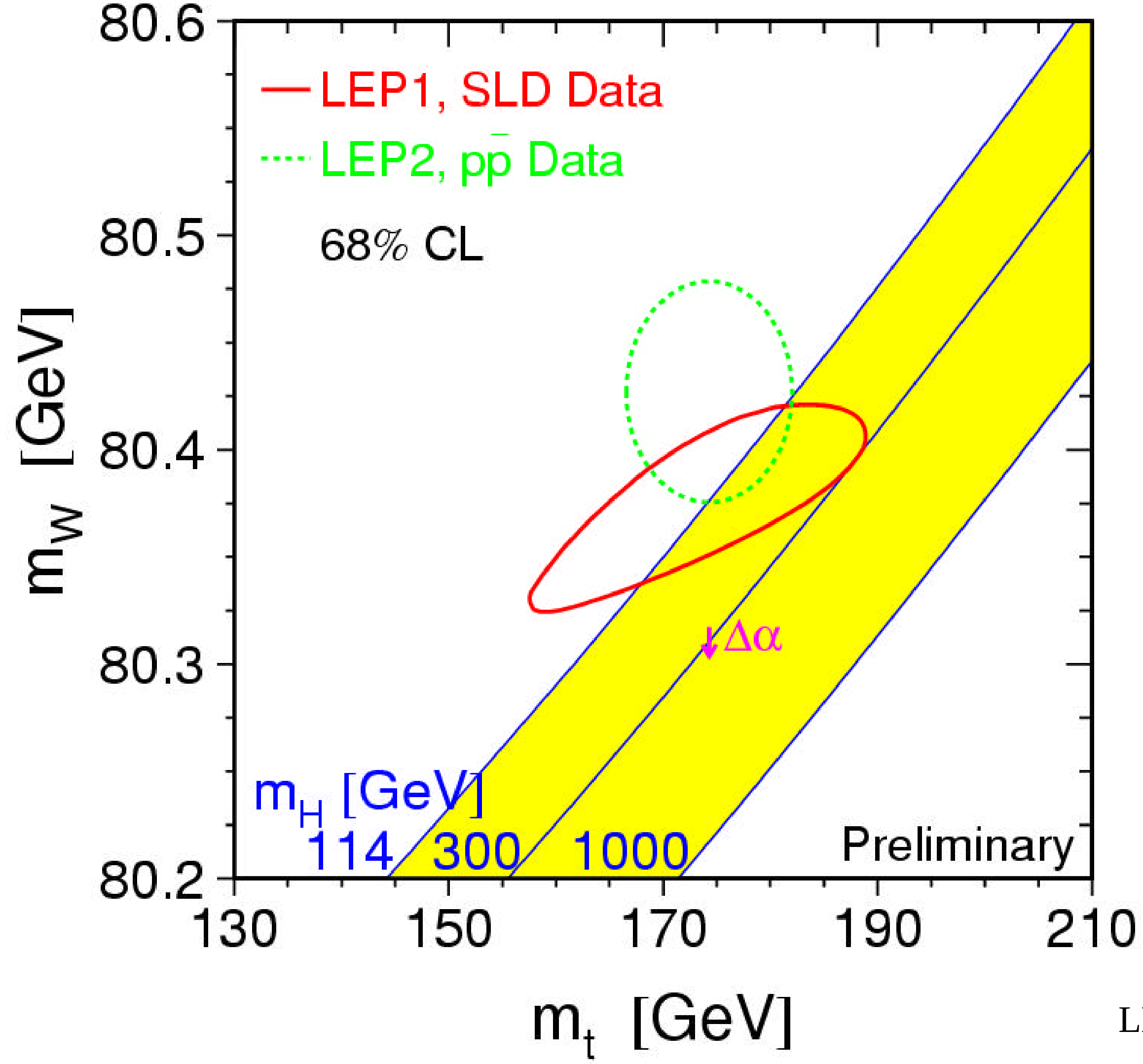
Bob Clare WIN ‘03

m_t Consistency



LEPEWWG/2003-01

m_W Also Key



LEPEWWG/2003-01

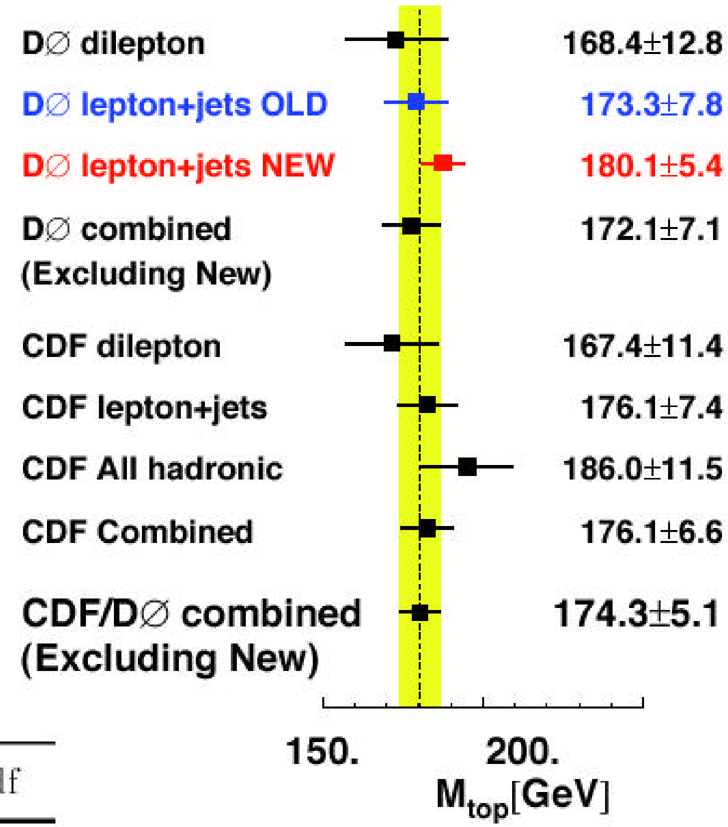
Top contribution

Preliminary CDF Run II Results

$$m_t = 177.5^{+12.7}_{-9.4} \pm 7.1(\ell + \text{jets})$$
$$m_t = 175.0^{+17.4}_{-16.9} \pm 7.9(\ell\ell)$$

New (Preliminary) D0 Run I Result

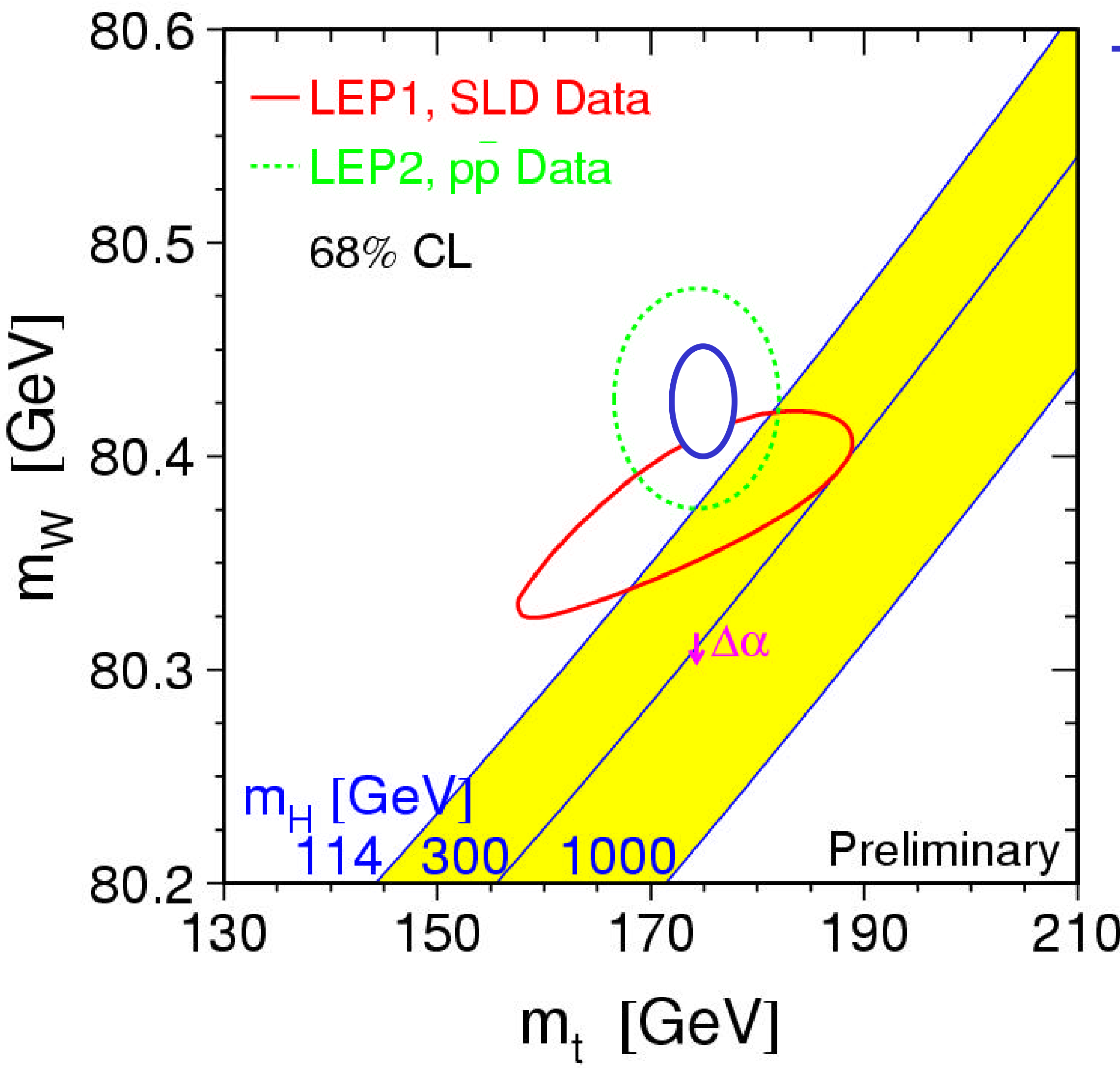
$$m_t = 180.1 \pm 3.6 \pm 4.0 \text{ GeV}$$



P. Renton hep-ph/0206231

fit	m_H GeV	χ^2/df
now: $\delta m_t = \pm$ 5.1 GeV, $\delta m_W = \pm$ 33 MeV	85^{+54}_{-34}	29 / 15
if $\delta m_t = \pm$ 2.0 GeV, $\delta m_W = \pm$ 33 MeV	83^{+38}_{-28}	29 / 15
if $\delta m_t = \pm$ 5.1 GeV, $\delta m_W = \pm$ 15 MeV	67^{+40}_{-27}	34 / 15
if $\delta m_t = \pm$ 2.0 GeV, $\delta m_W = \pm$ 15 MeV	50^{+21}_{-16}	35 / 15
if $\delta m_t = \pm$ 1.0 GeV, $\delta m_W = \pm$ 10 MeV	35^{+12}_{-10}	38 / 15

Future Prospects

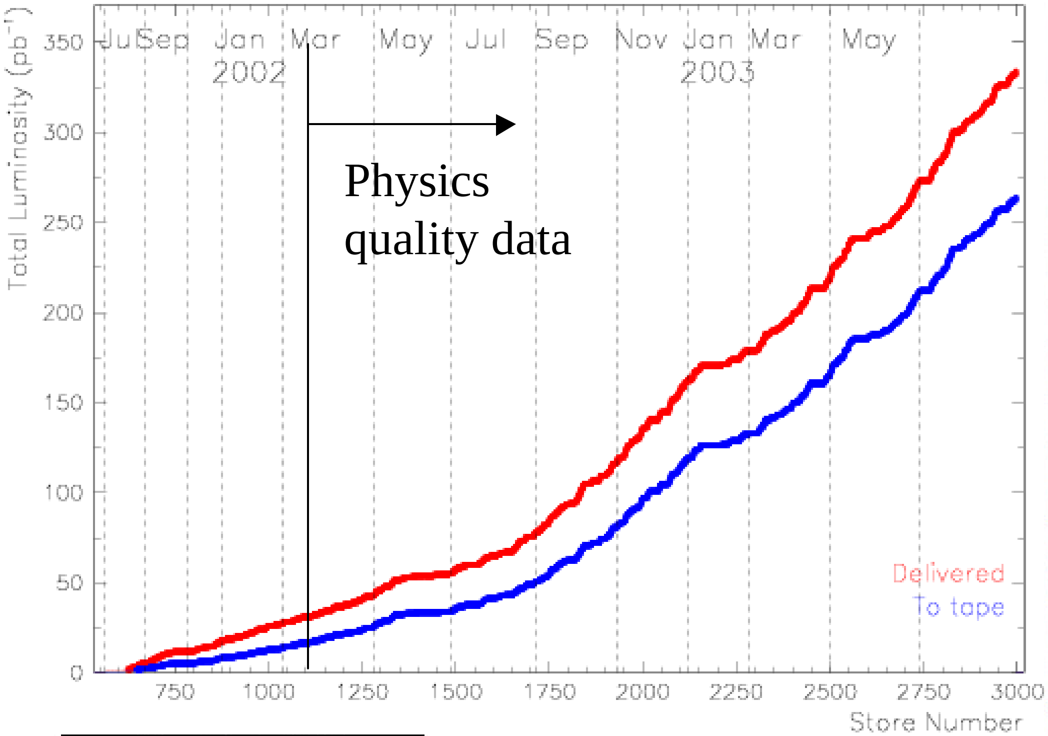


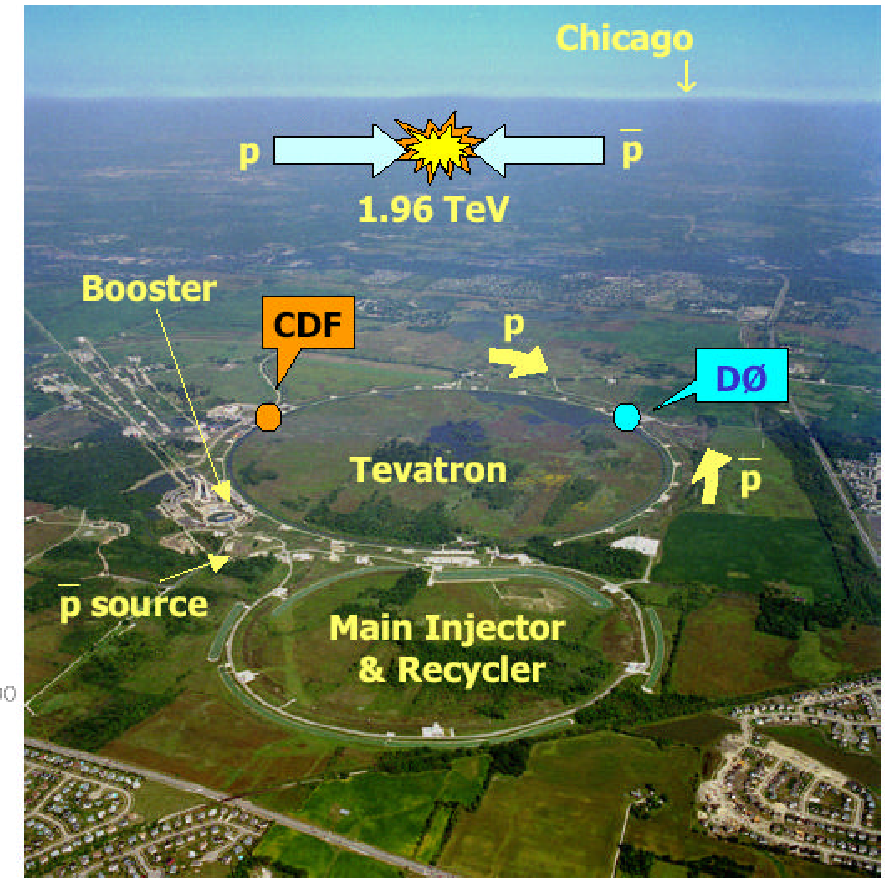
Possible future Tevatron/LHC measurement

~2 GeV δm_t

~15 MeV δm_W

The Tevatron





Integrated Luminosity (fb^{-1})				
	Design Projection		Base Projection	
	per year	Accum-ulated	per year	Accum-ulated
FY03	0.22	0.30	0.20	0.28
FY04	0.38	0.68	0.31	0.59
FY05	0.67	1.36	0.39	0.98
FY06	0.89	2.24	0.50	1.48
FY07	1.53	3.78	0.63	2.11
FY08	2.37	6.15	1.14	3.25
FY09	2.42	8.57	1.16	4.41

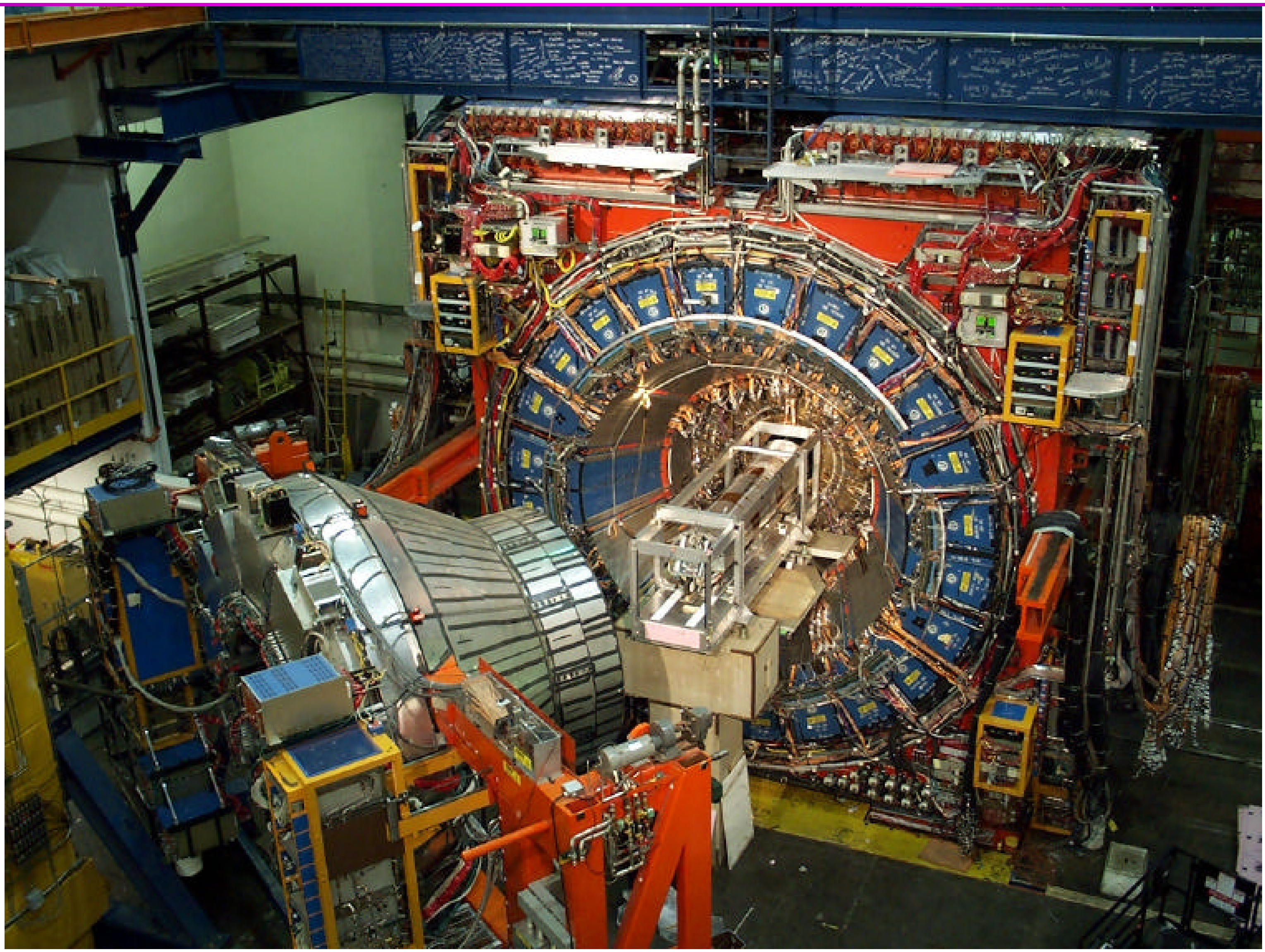
~330 pb^{-1} delivered to date

~260 pb^{-1} on tape

~180 pb^{-1} for l+jets mass w/ silicon now

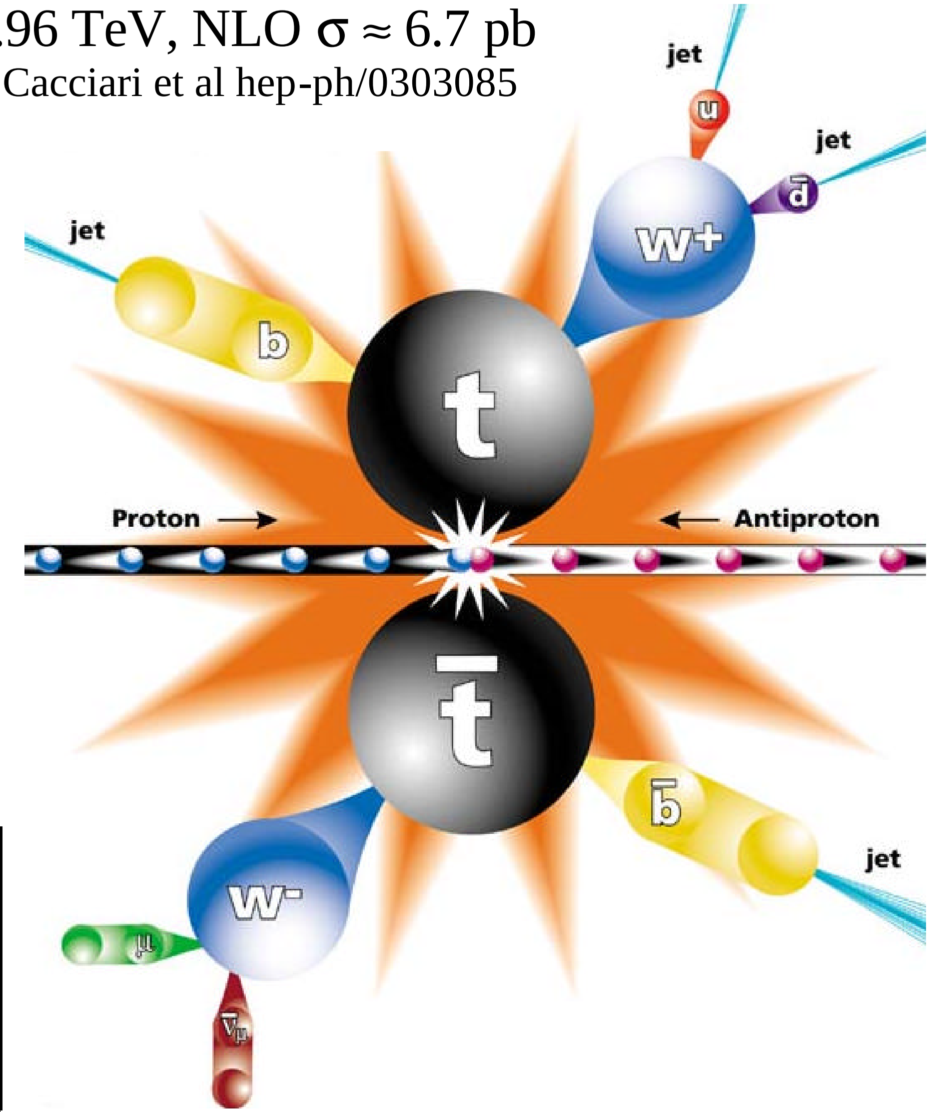
~500 pb^{-1} for Spring 2005 thesis?

Snapshot of CDF (Installing the SVX)



$t\text{-}\bar{t}$ Overview

- Production in p-pbar collisions at $\sqrt{s}$ = 1.96 TeV, NLO $\sigma \approx 6.7$ pb
  Cacciari et al hep-ph/0303085
- 85% q-qbar, 15% gluon fusion
- $\Gamma_t \approx 1.4$ GeV, $\tau \approx 10^{-24}$ s
- Leptons (e, μ) well measured
- Quarks (jets) poorly measured
  - And much QCD background
  - B quarks (mesons) taggable
- Neutrinos don't interact in detector
  - Measured indirectly

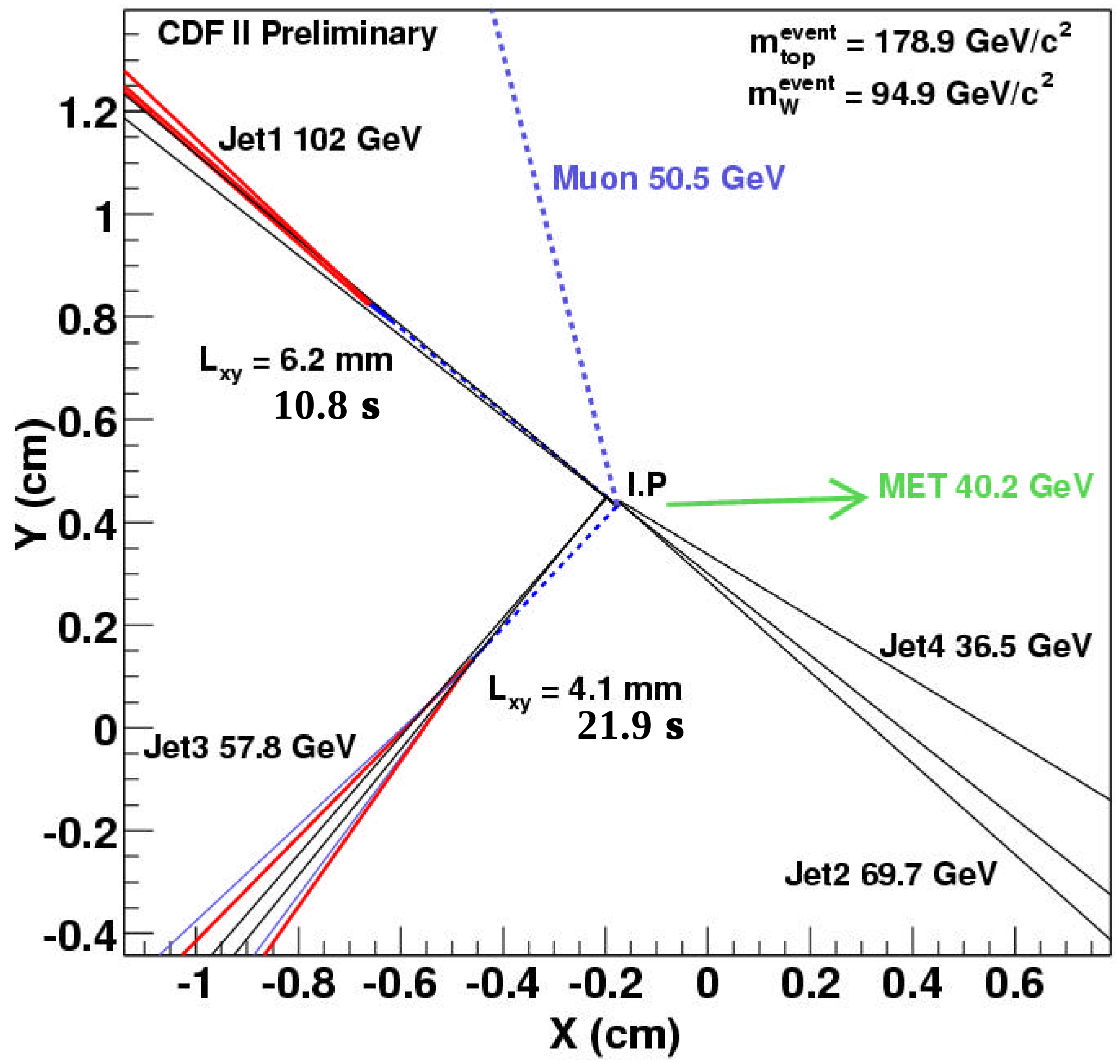


t-tbar Topologies

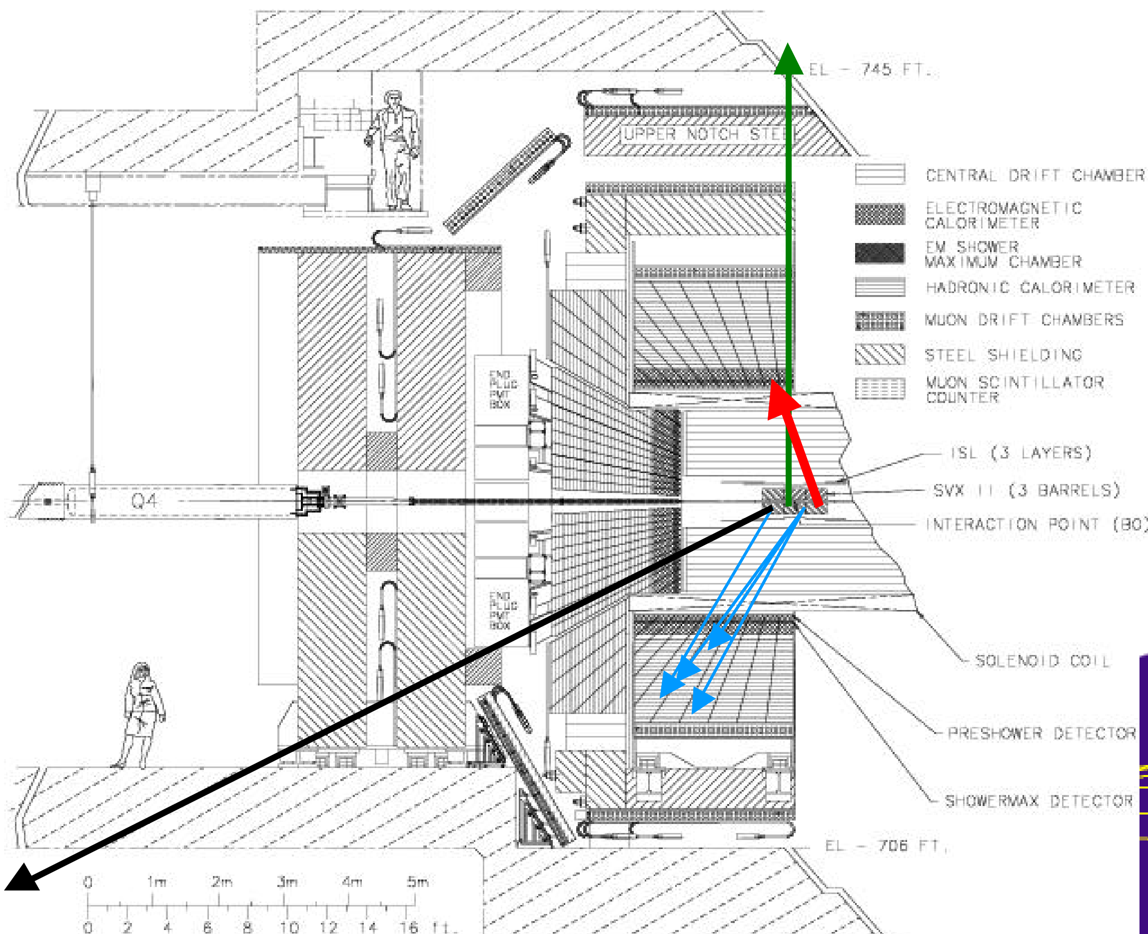
Dilepton (e, μ)	l+jets (e, μ)	All Hadronic	Other (τ's)
5%	30%	45%	20%

Event Selection (CDF Run II measurement)

- High E_T (20 GeV) e or μ
- High $\not{E}_T$ (20 GeV)
  - infer ν
- 4 High E_T jets
  - At least one w/ displaced vertex B tag
- Combinatorics – which jets are from t?
- Combinatorics and jet energy measurements make m_t a difficult measurement



CDF Detector



e’s – EM calorimeter

– tracking chamber

m’s – tracking chamber

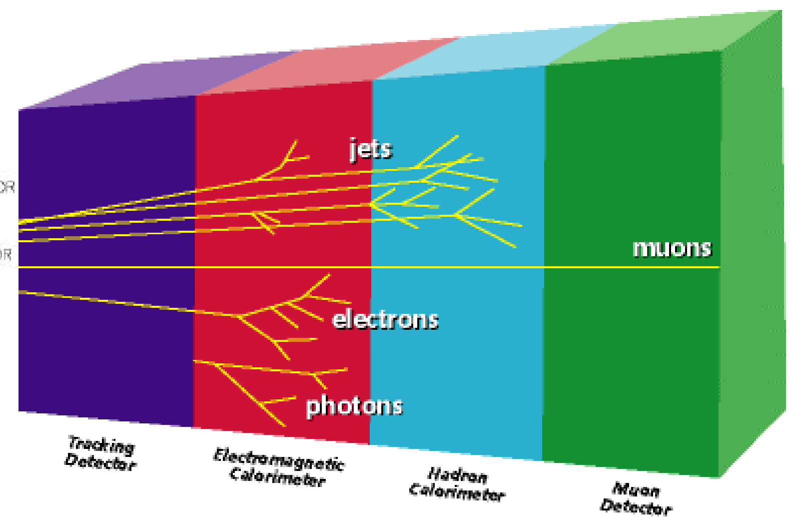
– muon chambers

Jets – calorimeters

B Jets – calorimeters

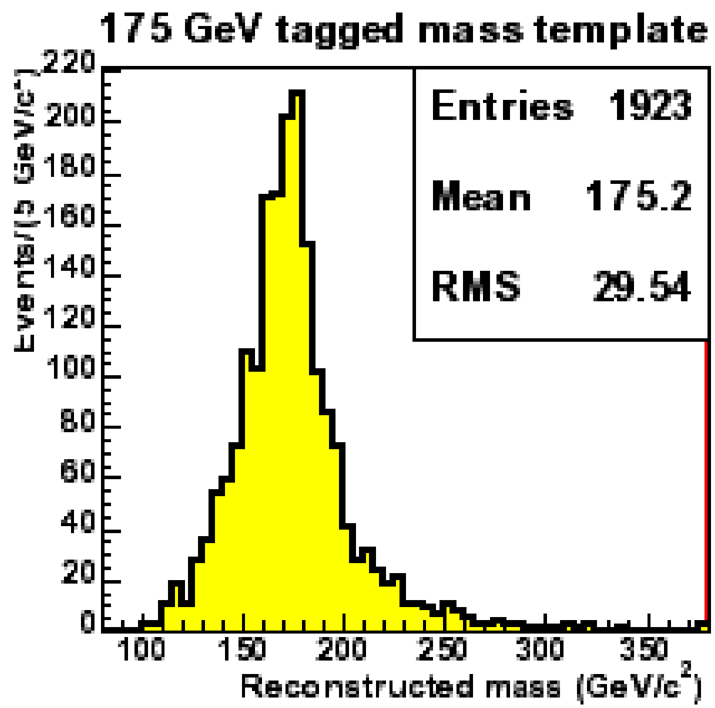
– silicon detectors

n’s – don’t interact in detector



Event by event reconstruction

- 4 jets, 1 central e or μ, large missing E_T, at least one displaced vertex b tag
- 2x3(x2) ways to assign jets to partons with one tag, 2(x2) for double
- Enough measurements to overconstrain system
- 2-C fit to find the (one) best combination (lowest χ^2)
- χ^2 cut to help reject backgrounds

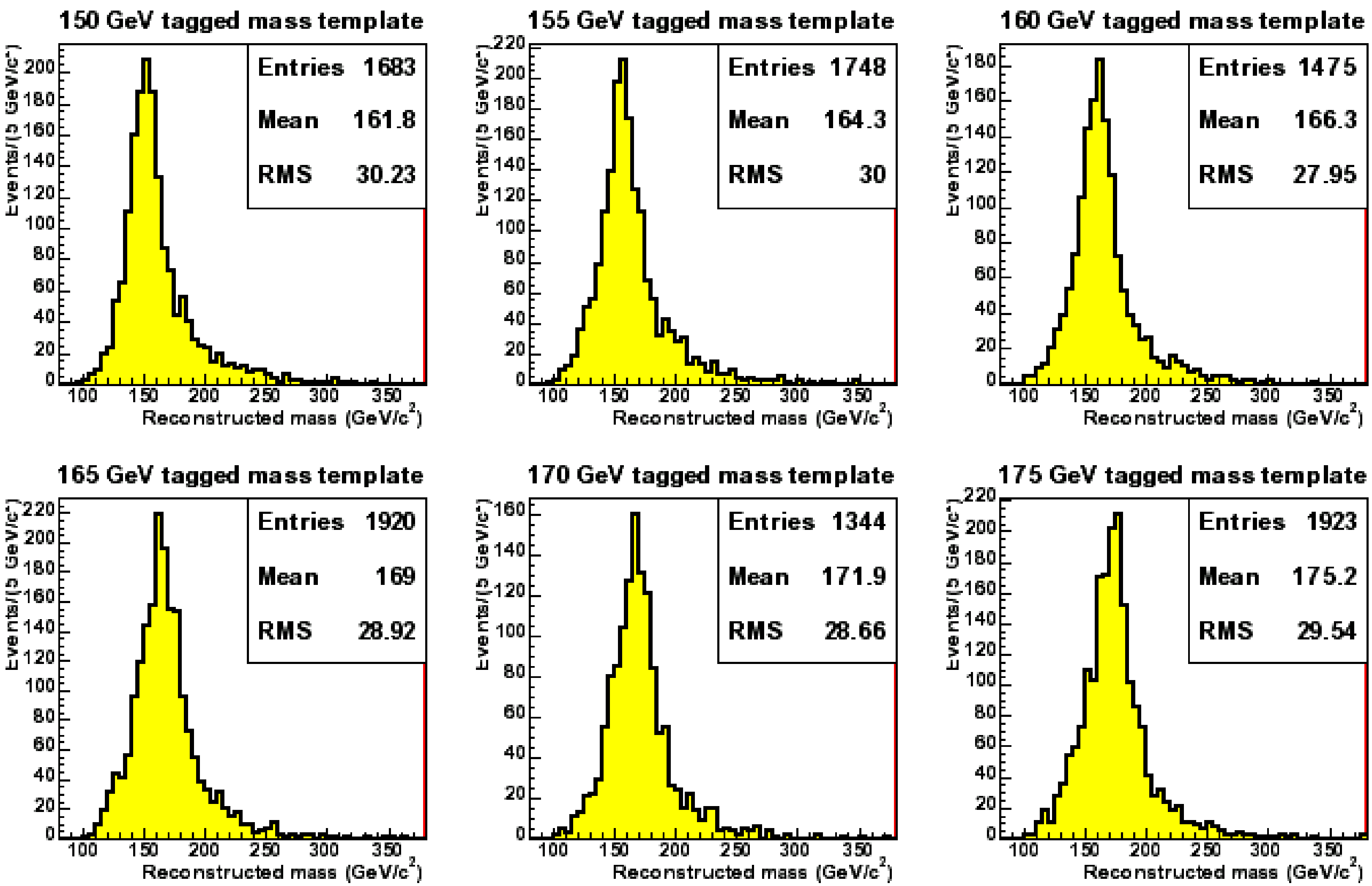


$$c^2 = \sum_{i=l,\,jets} \frac{(p_T^{i,fit} - p_T^{i,meas})^2}{s_i^2} + \sum_{j=x,y} \frac{(p_j^{UE,fit} - p_j^{UE,meas})^2}{s_j^2}$$

$$+ \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(M_{ln} - M_W)^2}{\Gamma_W^2} + \frac{(M_{bjj} - M_t)^2}{\Gamma_t^2} + \frac{(M_{bln} - M_t)^2}{\Gamma_t^2}$$

Build Mass Templates for Various Masses

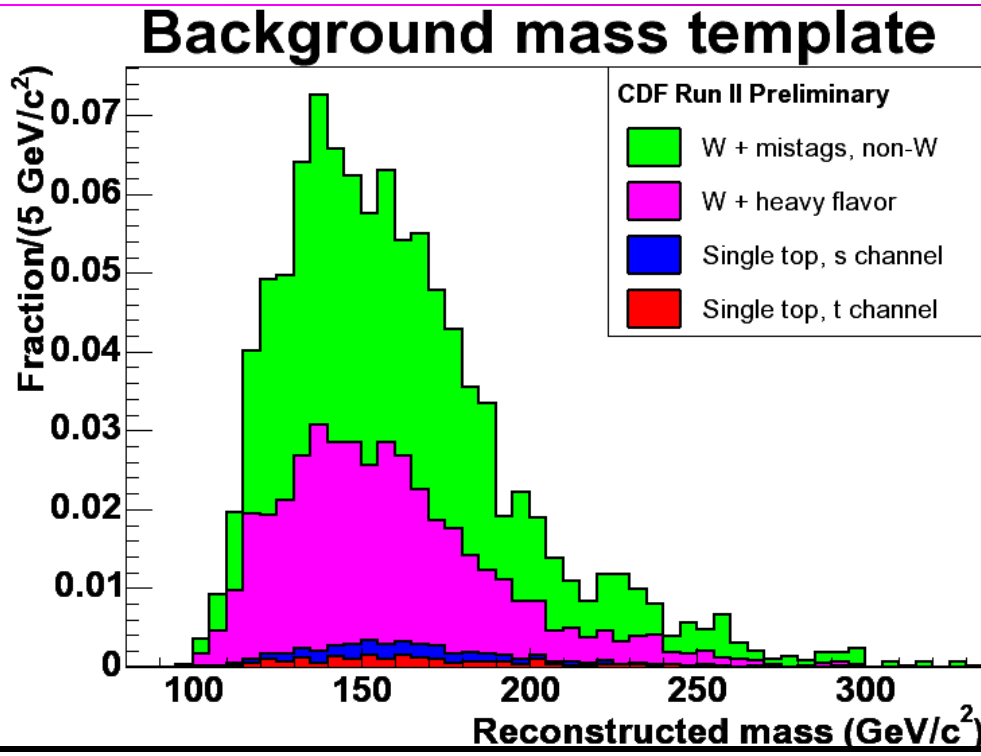
CDF Run II Preliminary



Backgrounds (For 22 Events in Data)

Source	Events	Approximate σ
W + jets (mistags)	2.25 ± 0.32	33 pb
Wbbar	1.71 ± 0.51	0.74 pb
Wccbar	0.72 ± 0.25	1.39 pb
Wc	0.63 ± 0.13	1.96 pb
WW/WZ	0.20 ± 0.06	
Non-W (QCD)	2.4 ± 0.36	Very Large
Single top	0.4 ± 0.04	
Total	8.31 ± 0.76	

Compare to ttbar cross section of ~7 pb

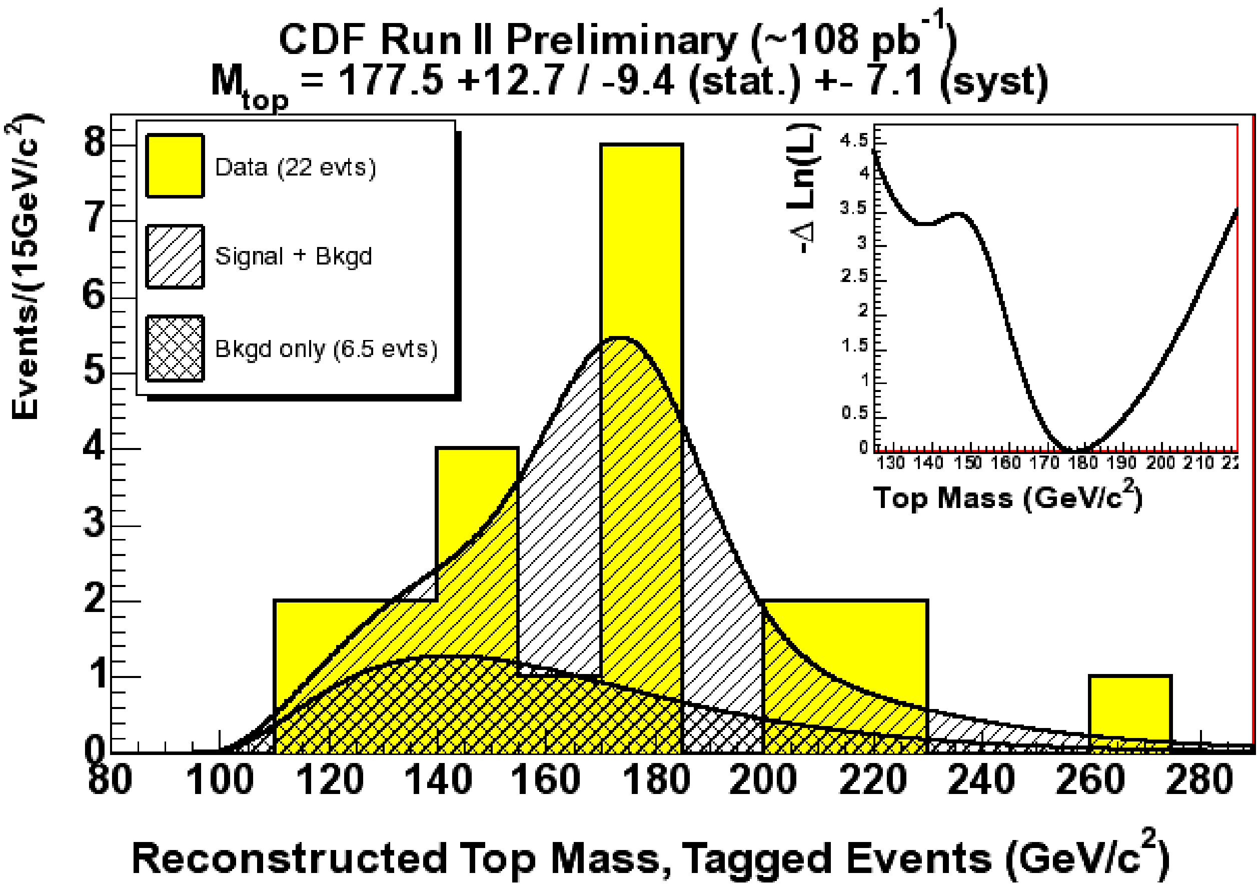


- b tagging involves a choice between efficiency and fake rate
  - Choice determines background composition
- Overall S:B is 2.7:1
  - 16:6

Background events with $\chi^2 < 10$		
Mass Template Source	Background Source	Number of Events
W + jets (mistags)	Mistags, QCD	3.42 ± 0.36
Wbbar	Wbbar, Wccbar, Wc, WW/WZ	2.26 ± 0.41
Single top: s channel		0.16 ± 0.01
Single top: t channel		0.11 ± 0.01
Total		5.94 ± 0.55

Final Fit: Shape Comparison of Data to MC Gives m_t

- Signal shape parameterized, and as function of top mass.
- Background shape parameterized
- Unbinned likelihood fit to parameterized templates, with a background constraint



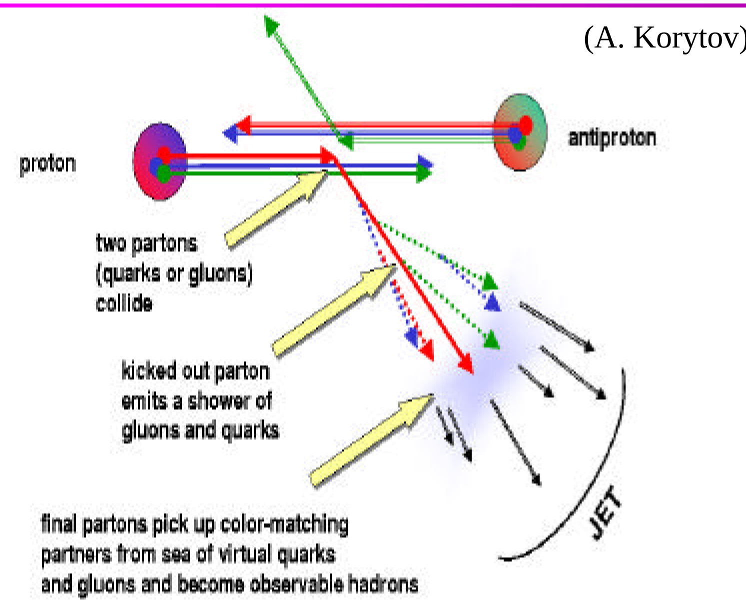
Systematics

- Jet energy measurement leads to dominant systematic
- Initial State and Final State Radiation (ISR/FSR) since gluons affect jet energy, top and W mass, etc.
  - Run I numbers (turn on, off) for now.
- PDF's use CTEQ6M eigenvector sets

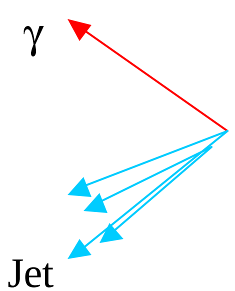
Source of Syst.	ΔM_{top} (GeV/c^2)
Jet Energy	6.2
ISR	1.3
FSR	2.2
Generators	0.5
PDFs	2
Other MC modeling (Jet Resolution, p_T^{top})	1
Background Shape	0.5
b-tagging	0.1 (Run I)
Total	7.1

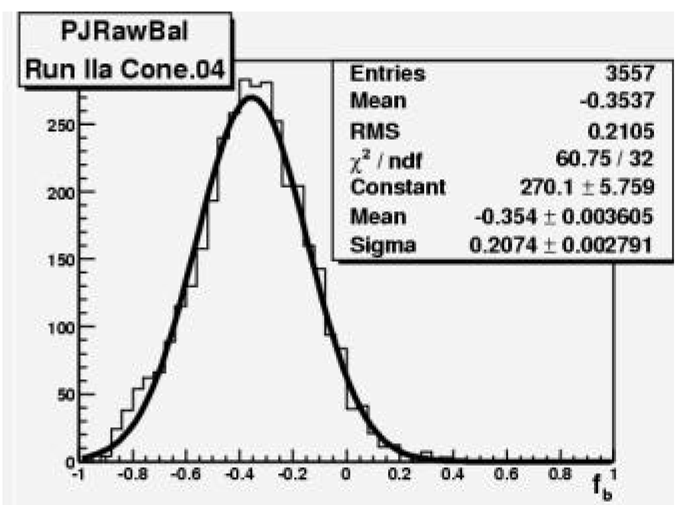
Understanding Jets

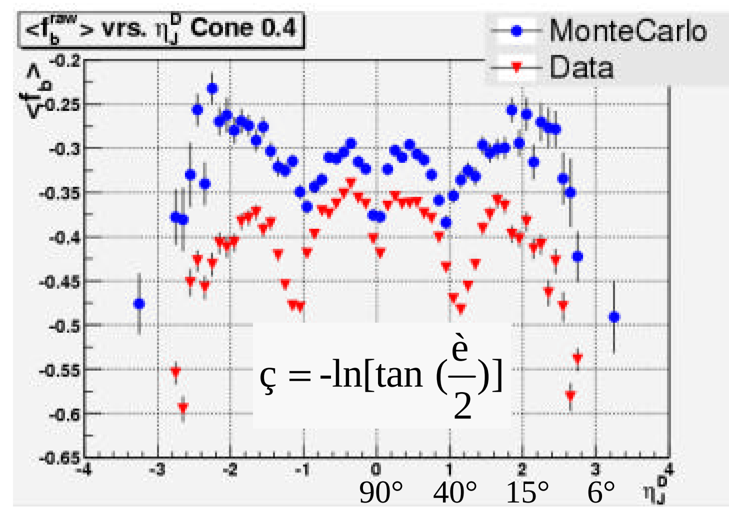
- Quarks and gluons appear in the calorimeter as jets: collection of hadrons
  - Mostly π's
- Reconstruct m_t in terms of parton energies, want to correct jets back to parton level
- Difficult to calibrate at low particle energies typical in jets
  - Cracks in detector, Non-linearities
  - Understanding fragmentation
  - Out of cone energy



$$f_b = \frac{P_T^{Jet}}{P_T^{ã}} - 1$$

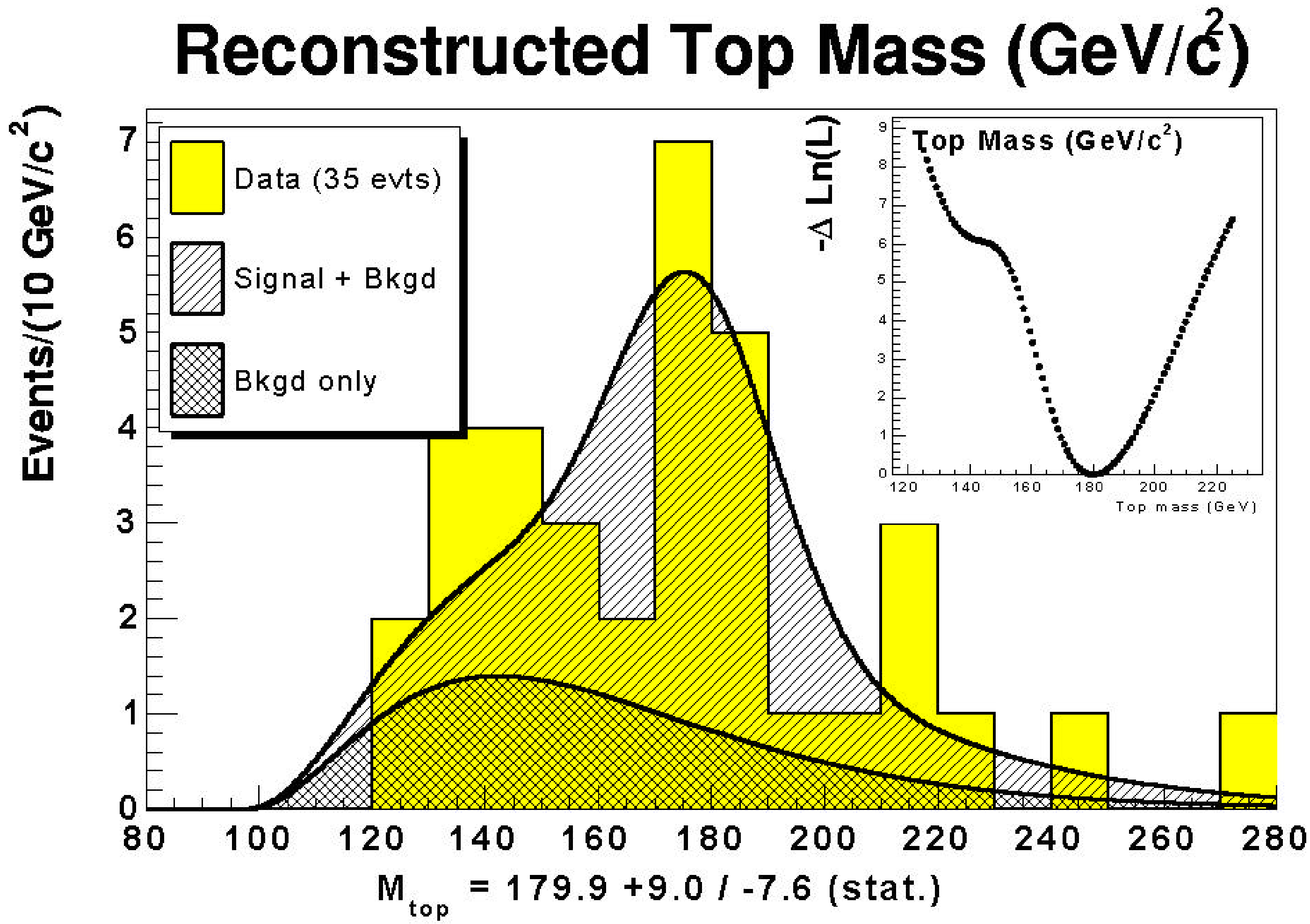






Traditional Analysis Continues

~180 pb^{-1}



New D0 Run I Top Mass Analysis

- Use all of the information you measure well, integrate over things you don't measure well.
- Compare to our best knowledge of the physics – compare to SM differential cross sections.
- Integrate cross sections over quark energies, using MC-extracted transfer functions to connect to measured jet energies.

$$P_{t\bar{t}}(x, m_t) = \frac{1}{s_{tot}} \int ds\,(y, m_t) dq_1 dq_2 f(q_1) f(q_2) W(x, y)$$

$$|\mathrm{M}|^2$$

x measured quantities (e.g. jets)

y matrix element quantities (e.g. partons)

f(q) parton distribution functions

W(x,y) transfer functions

q_1, q_2 incoming quark energies

D0 l+jets (1998) $m_t = 173.3 \pm 5.6$ (stat) ± 5.5 (syst) GeV/c^2

D0 l+jets (2003) $m_t = 180.1 \pm 3.6$ (stat) ± 4.0 (syst) GeV/c^2

Traditional CDF Template Method vs. New D0 Matrix Element Method

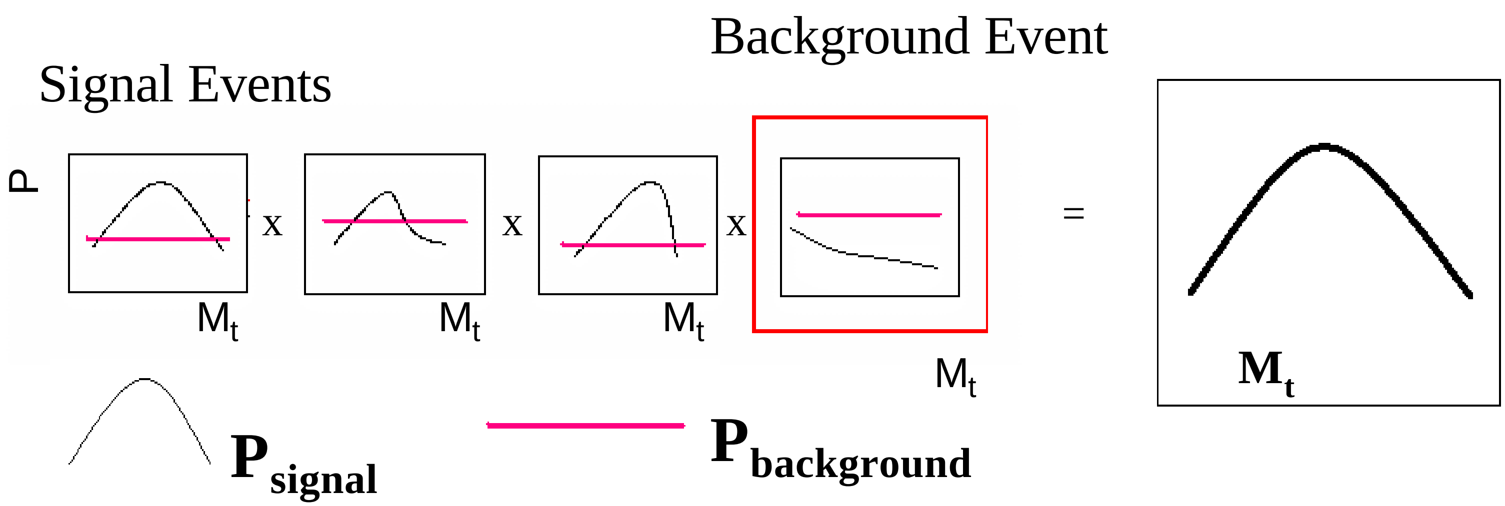
Traditional CDF (Template)

- One m_t per event, equal weight.
- Single best-fit (χ^2) combination.
- Series of eight levels of jet corrections, get mean correct and assume Gaussian shape.
- Global m_t fit from likelihood fit of data to signal and background templates

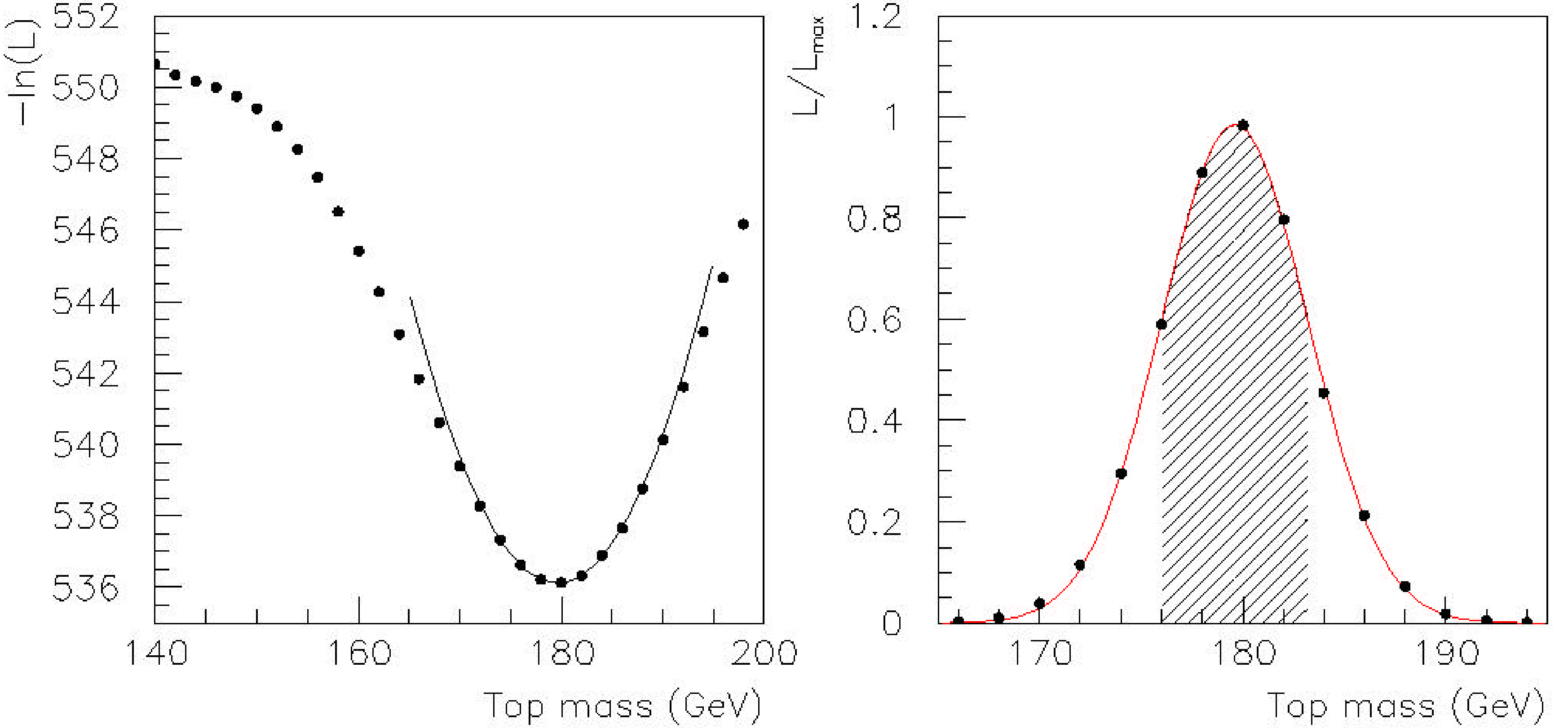
New D0 (Matrix Element)

- $P(x : m_t)$ for each event, based upon comparison of fifteen kinematic variables (x) to SM matrix elements
- All combinations weighted according to signal probability, and events combined according to signal probability
- Transfer functions connecting parton energies to jet energies in detail
- Global m_t fit from joint likelihood of signal (mass-dependent) and background (mass-independent) probabilities.

Global m_t Fit Schematically: Combining Events



D0 Results From Data (l+jets With No B Tag Requirement)



M_t= 180.1 ± 3.6 GeV (stat)

Compared with 5.6 GeV statistical error from previous D0 mass analysis. The statistical error you'd expect from the old D0 analysis with a factor of 2.4 more data.

22 events in data: 12 ± 3 signal (from fit), 10 ± 3 background

Systematics at D0

- D0's new analysis has a significantly smaller systematic due to jet energies.
  - More detailed connection between jets and partons (transfer functions)
- Other systematics smaller as well
  - Using more event information, and combining events and combinations more effectively

D0 (1998)

TABLE XXIX. Systematic uncertainty summary.

	LB (GeV/c^2)	NN (GeV/c^2)	Average (GeV/c^2)
Jet energy scale	4.2	3.8	4.0
Generator			
$t\bar{t}$ signal	1.9	1.9	1.9
VECBOS flavors	2.5	2.5	2.5
Noise/MI	1.3	1.3	1.3
Monte Carlo stat.	0.6	1.1	0.85
LB/NN diff	0.8	0.8	0.8
Likelihood fit	1.0	1.0	1.0
Total	5.6	5.4	5.5

Phys. Rev. D {58} 052001 (1998)

D0 (2003)

Systematic Uncertainties for top quark mass

Determined from MC studies with large event samples:

Signal model	1.5 GeV/c²
Background model	1.0 GeV/c²
Noise and multiple interactions **PRD 58 52001, (1998)**	1.3 GeV/c²

Determined from data:

Jet Energy Scale	3.3 GeV/c²
Parton Distribution Function	0.2 GeV/c²
Acceptance Correction	0.5 GeV/c²

Total systematic error 4.0 GeV/c^2

Applying D0's Methods at CDF

- Very similar methods have been proposed by CDF members (Kondo) and others (Dalitz and Goldstein)
  - Studied in Run I at CDF, but no mass measurement published.
  - Dynamical Likelihood Method work well underway in Run II
- No magnetic field at D0 Run I
  - Muons poorly measured, integrated over.
- Poor or no silicon coverage at D0 Run I
  - 2003 mass analysis didn't use displaced vertex tags.
  - Easy to use binary SVX tags at CDF, more in keeping with the method to use a tag probability. Either way should help dramatically reduce backgrounds. But, there may be more backgrounds to consider (more matrix elements).
- Straightforward to add extra signal and background matrix elements.
- More difficult to incorporate extra matrix element with gluon radiation, either just extra diagrams or full NLO calculation

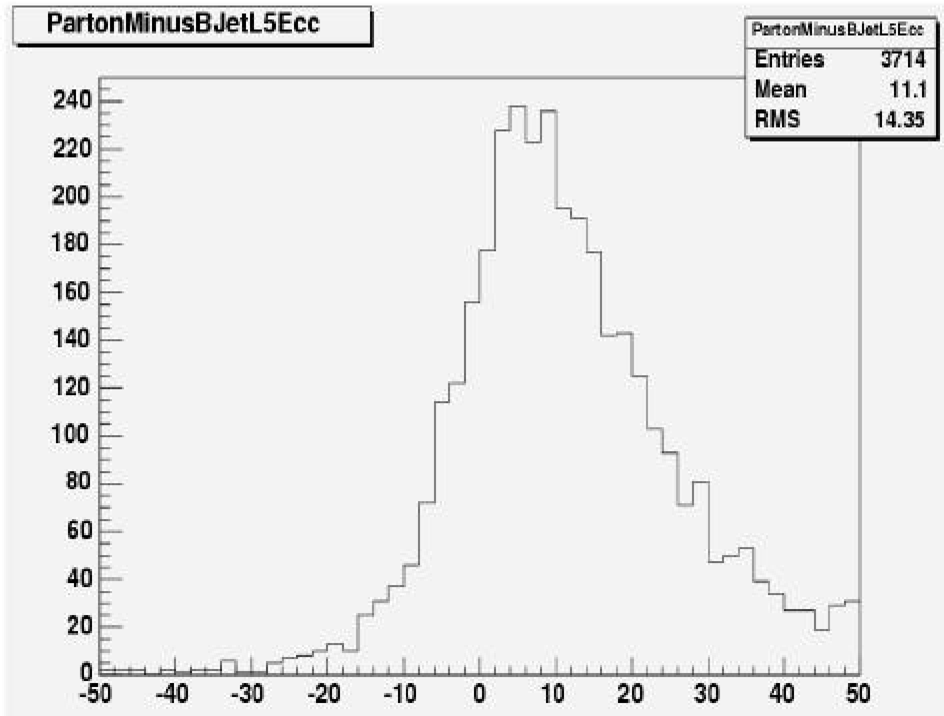
D0-Style Transfer Functions at CDF

- We have eight levels of jet corrections at CDF to get from jets back to parton-level quantities.

•In general, their goal is to get the mean right, while assuming a gaussian shape

•Our transfer functions use jets that have been corrected back to particle-jet level (detector effects removed) (level 5 of 8)

•The goal is to start with partons, and accurately model the distribution of jet energies (shape as well as mean)



$E_{parton} - E_{jet}$ (GeV)

for B jets from ttbar MC

Transfer Function $W(E_{parton}, E_{jet})$

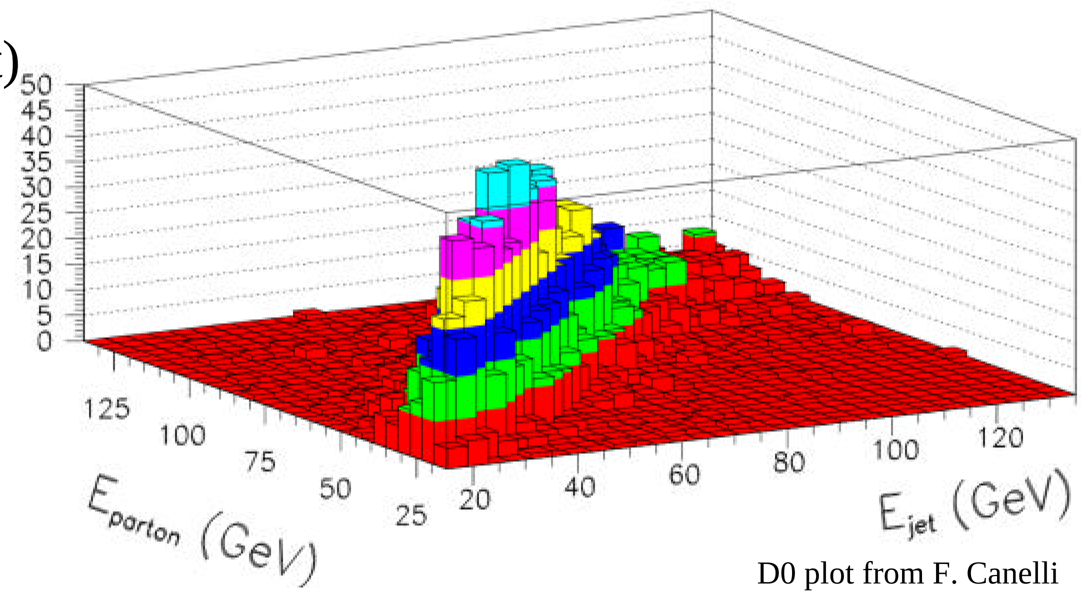
$$n(E_{jet}, E_{parton})dE_{jet}dE_{parton} = n(E_{parton})dE_{parton}W(E_{parton}, E_{jet})dE_{jet}$$

where

$n(E_{parton})$ is the (process dependent) distribution of parton energies

$W(E_{parton}, E_{jet})$ is the probability distribution to have E_{jet} given a E_{parton}

So, we hope to separate the process-dependent $n(E_{parton})$ from the largely process-independent $W(E_{parton}, E_{jet})$



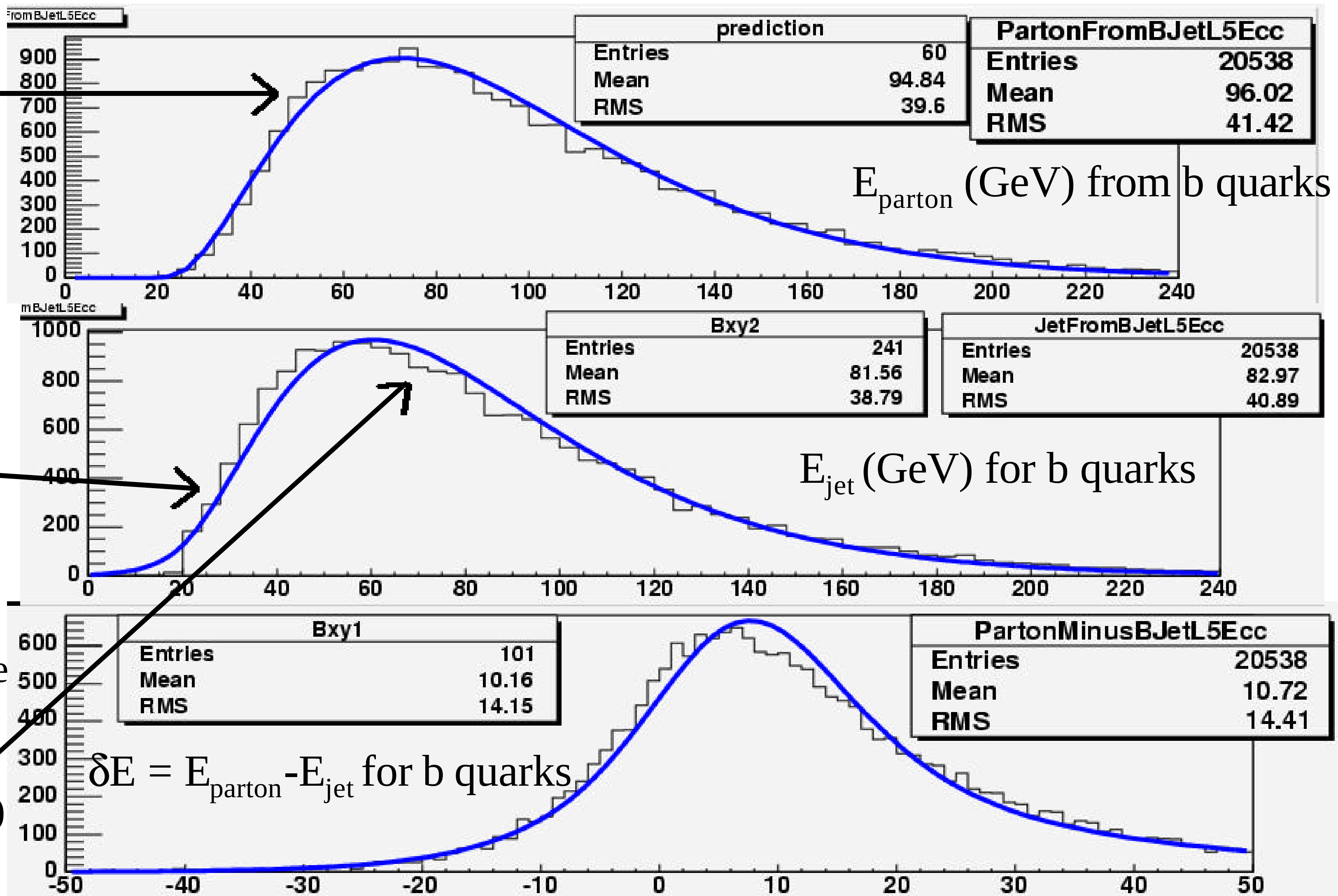
D0 plot from F. Canelli

$$d_E = E_{parton} - E_{jet}$$

$$F(d_E) = \frac{1}{\sqrt{2p}\,(p_2 + p_3 p_5)}\left[\exp\frac{-(d_E - p_1)^2}{2p_2^2} + p_3 \exp\frac{-(d_E - p_4)^2}{2p_5^2}\right]$$

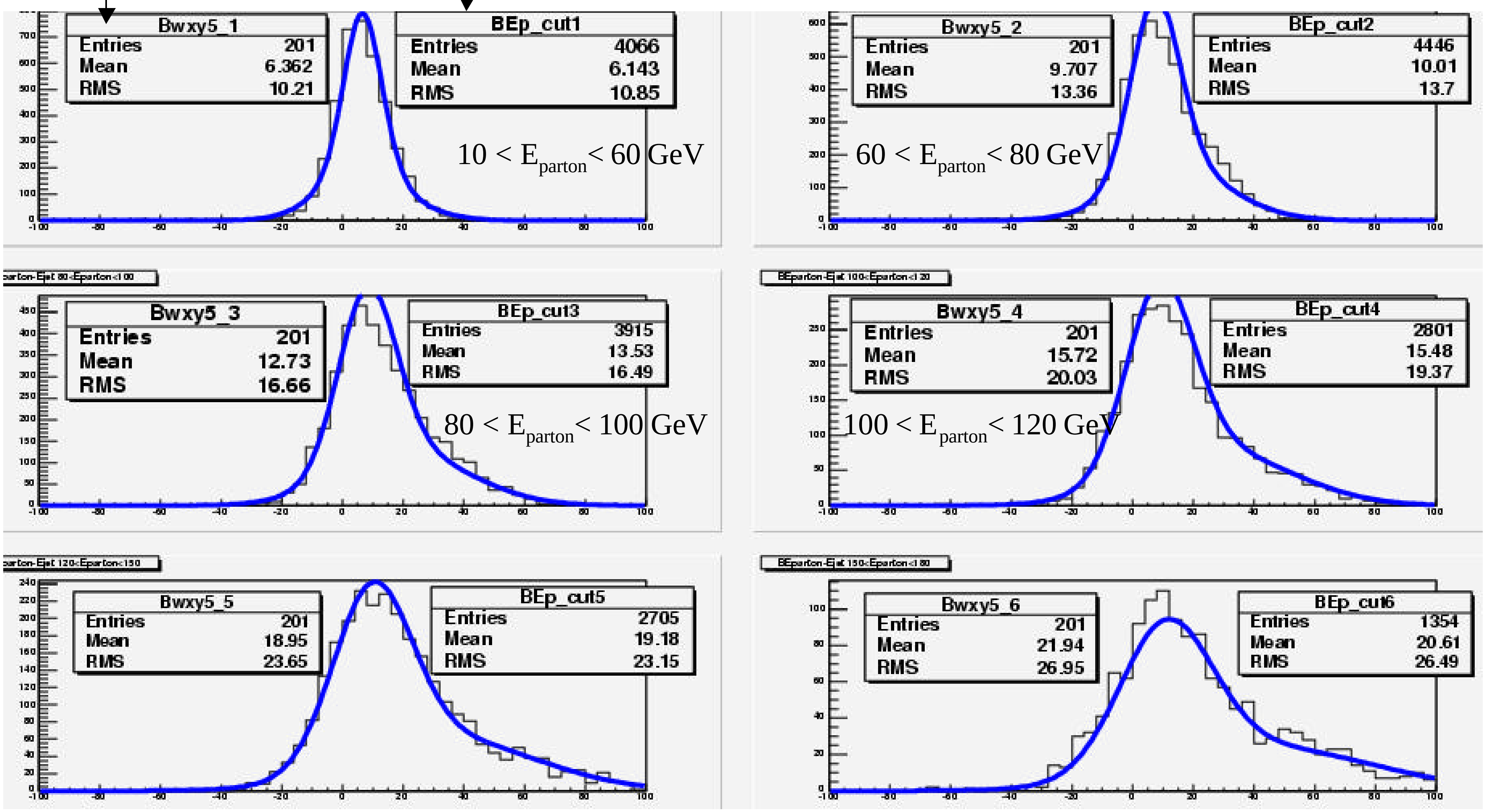
Testing the transfer functions

Parton information along with the transfer functions (previous page) allow us to make predictions (**blue curves**) of jet level quantities, and compare with simulation (histograms)



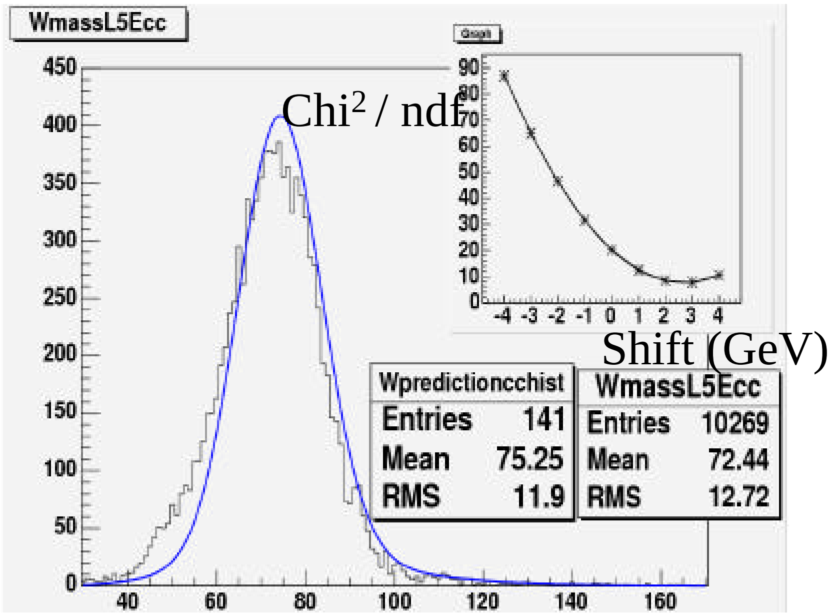
$\delta E = E_{parton} - E_{jet}$ (GeV) for b quarks

prediction simulation, reconstruction

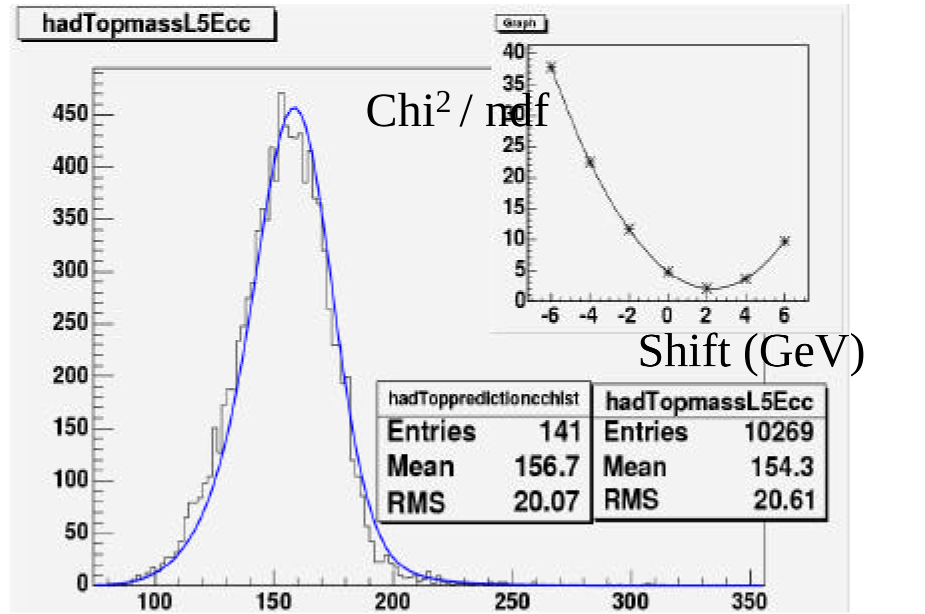


$120 < E_{parton} < 150$ GeV $150 < E_{parton} < 800$ GeV

Hadronic W and top mass from transfer functions – correct combination



Hadronic W mass (GeV)



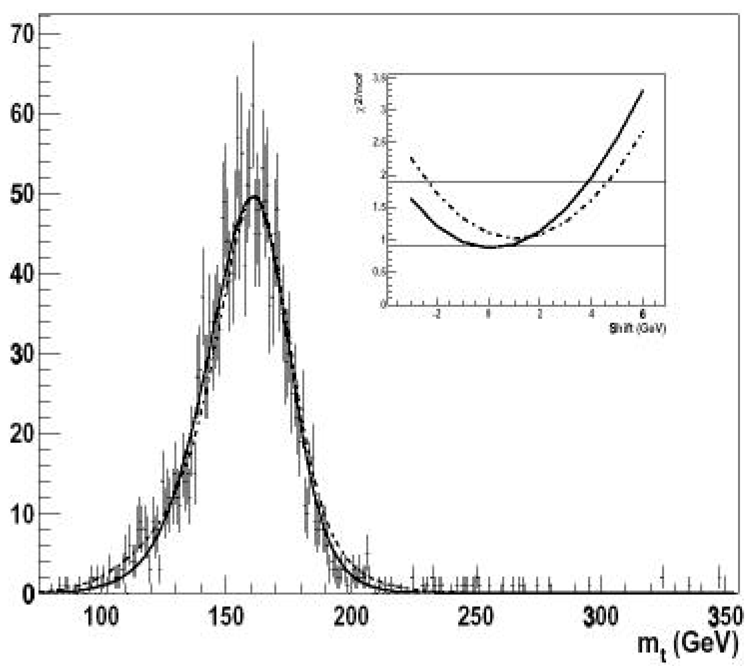
Hadronic top mass (GeV)

- Histogram from simulated, reconstructed Herwig jets.
- **Blue curve** is prediction from transfer function, using parton level Herwig.
- Inset is chi^2 as we shift the histogram against the prediction.
- Prediction is systematically high.

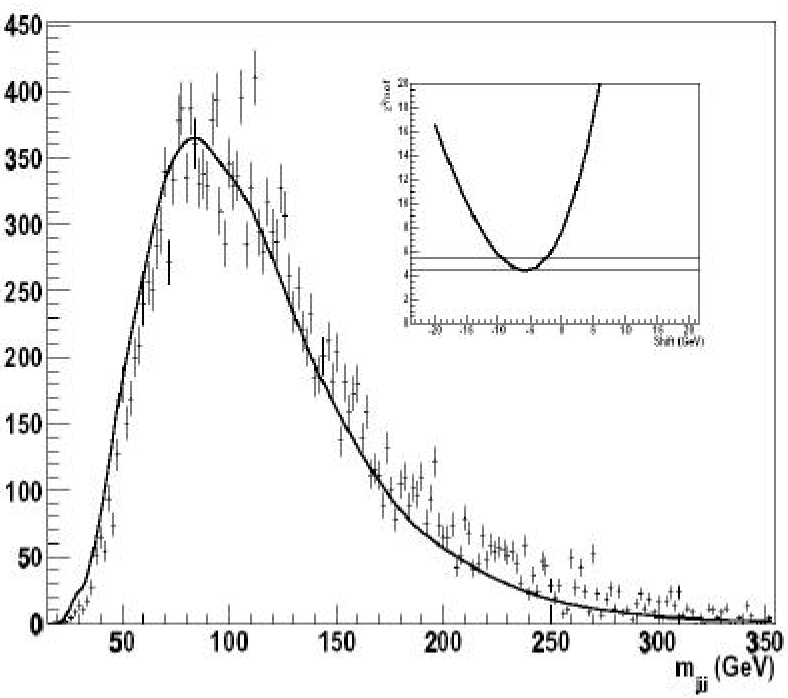
D0 transfer function tests

- Examples of the transfer functions D0 used for their analysis
- D0 saw a small bias also and was able to show that it didn't significantly affect the final top mass measurement (took a 0.5 GeV shift)
- Showed that ttbar transfer functions worked with background samples

ttbar MC events, hadronic top mass



W+jets MC events, 3 jet invariant mass



Expected reach with ~500 pb^{-1}

- 1-D Template Method, Run I CDF Method
  - Stat error 4.1 – 5.0 GeV (scale mean expected Run II error, scale current Run II error)
  - Syst error: with no brand new methods (W->qq, Z->bb calib) perhaps 5.0 GeV, with new methods, and reinterpretation of ISR/FSR, perhaps 3.0 GeV
  - Total error 5.1 – 7.1 GeV
- Matrix element method
  - Stat error 2.6 – 3.2 GeV (scale CDF error by factor of $\sqrt{2.4}$ more stat power)
  - Syst error – scale template method systematics by 0.73?
    2.2 – 3.7 GeV (or perhaps as large as template method, 5.0 GeV)
  - Total error 3.4 – 4.9 GeV (or 5.9 GeV)
- The lower statistical error is of short term interest (while statistics are still very limited)
  - Always nice to make your statistical error as small as possible
- Possibility for smaller systematics intriguing for the medium and long-term.

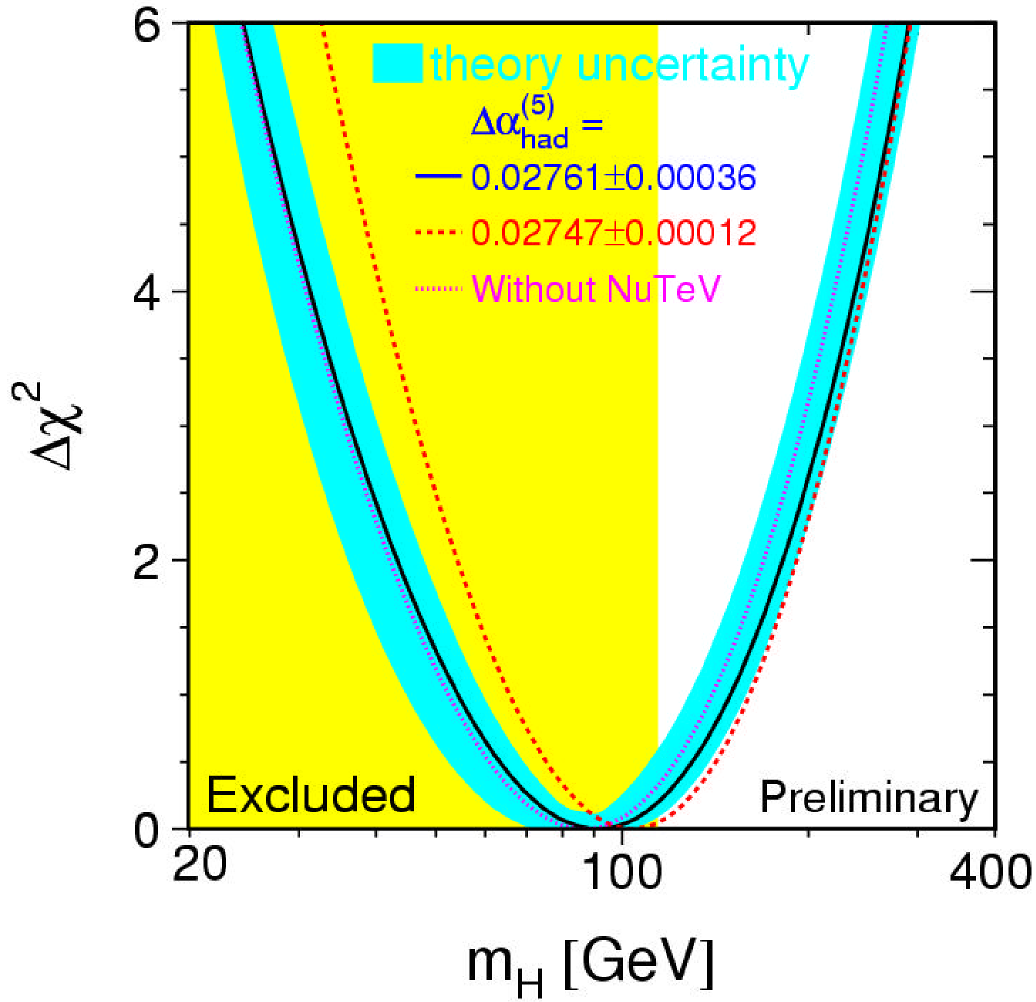
Summary

- The top mass is interesting in and of itself
- Especially interesting as a precision EW observable
  - Constrain SM, predict SM Higgs mass
  - Constrain physics beyond the SM
- I've participated in a template based mass analysis
  - $m_t = 177.5^{+12.7}_{-9.8}$ (stat) $\pm$ 7.1 (syst) GeV/c^2 (108 pb^{-1})
- Will continue to contribute to important tools like γ-jet balancing.
- Will pursue a matrix-element based analysis with the prospect of substantially improving the statistical power of the data we collect while also lowering the systematic uncertainty.
  - m_t = 1xx.x $\pm$ 2.6 (stat) $\pm$ 3.7 (syst) GeV/c^2 ?? (500 pb^{-1})

Backup Slides

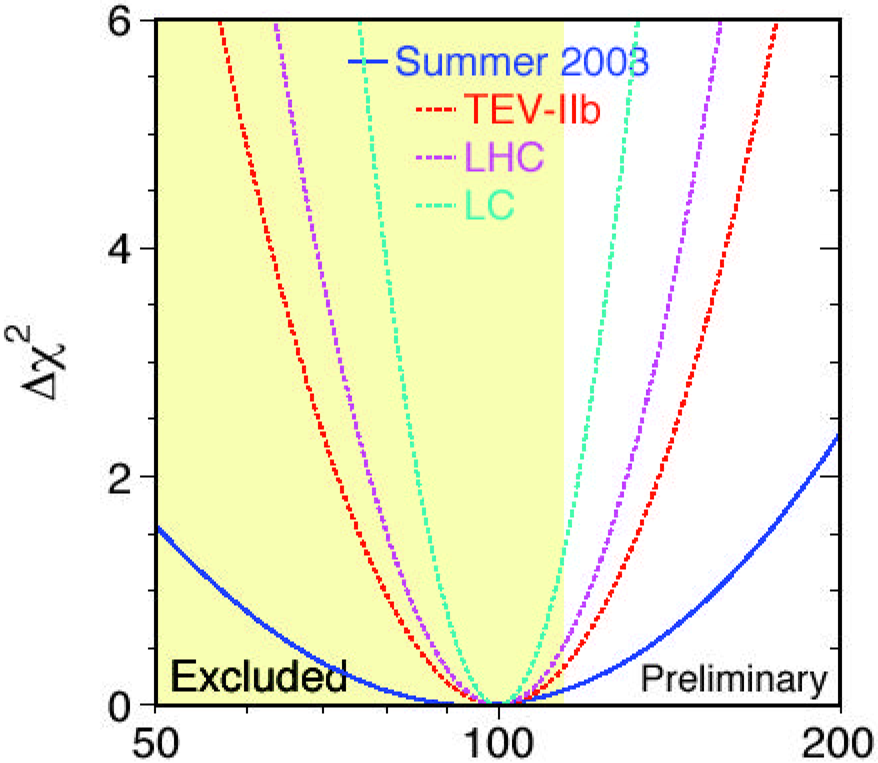
Constrain m_H

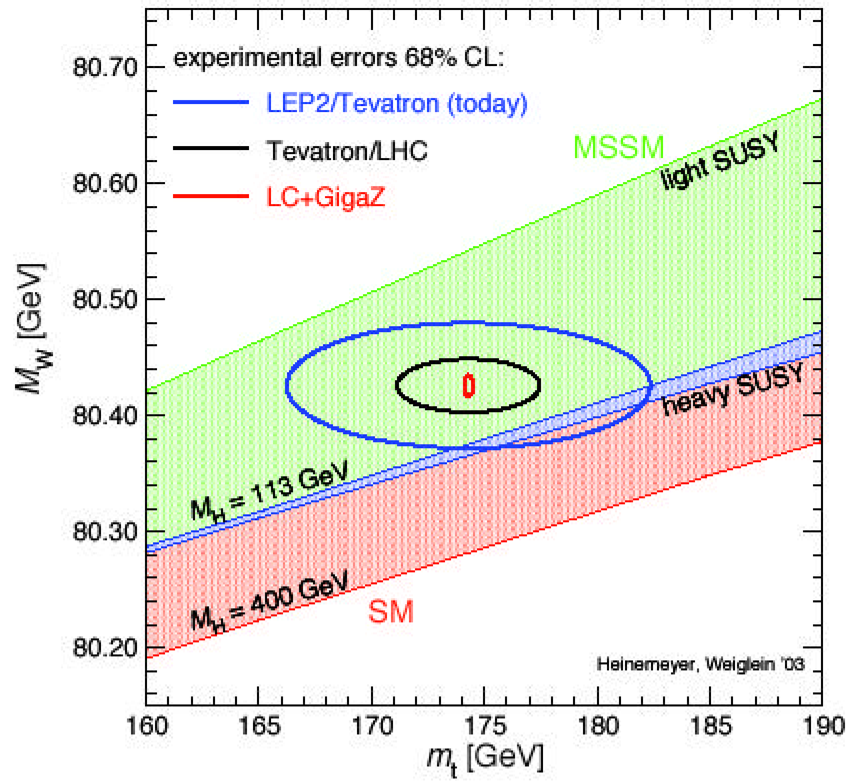
m_H best fit 96^{+60}_{-38} GeV, <219 GeV 95% CL



LEPEWWG/2003-01

Looking to the Future



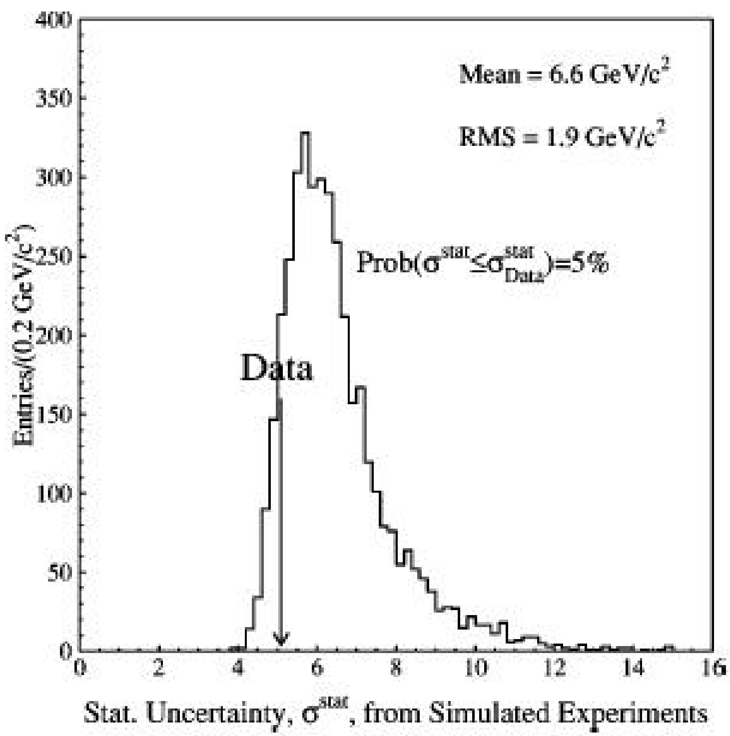


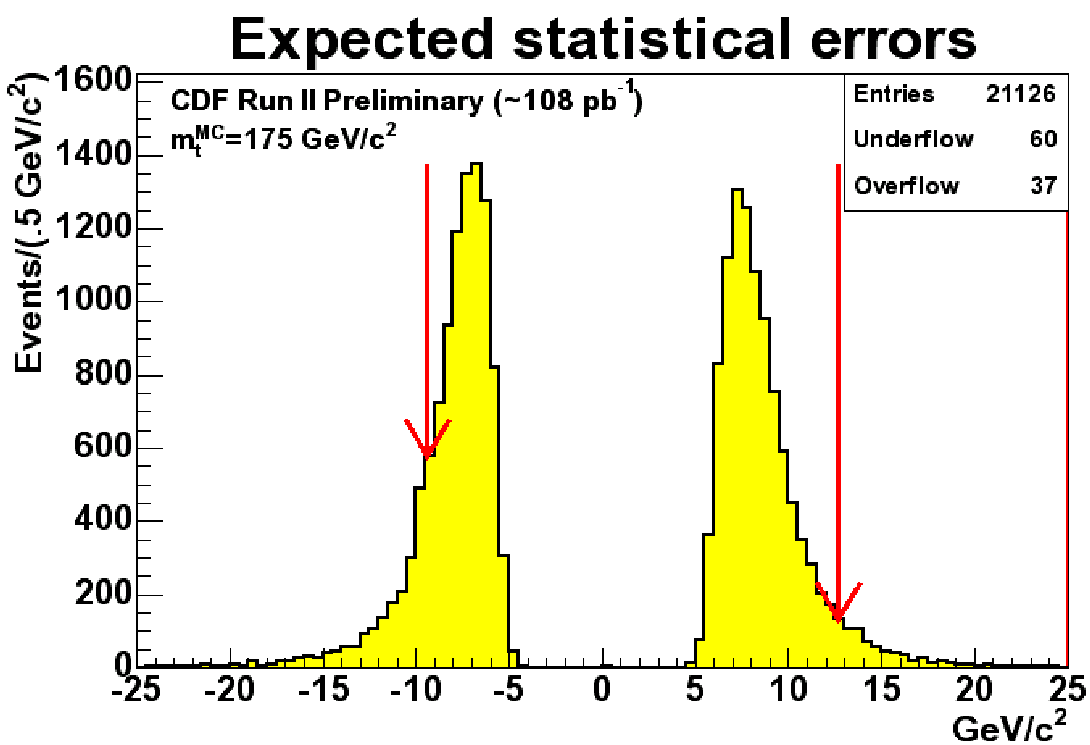
Bob Clare
Win 03

	now	Run IIA	Run IIB	Run IIB*	LHC	LC	GigaZ
$\delta \sin^2\theta_{eff}^{lept}(\times 10^5)$	17	78	29	20	14–20	(6)	1.3
δm_W [MeV]	33	27	16	12	15	10	7
δm_t [GeV]	5.1	2.7	1.4	1.3	1.0	0.2	0.13
δm_H [MeV]	—	—	$O(2000)$		100	50	50

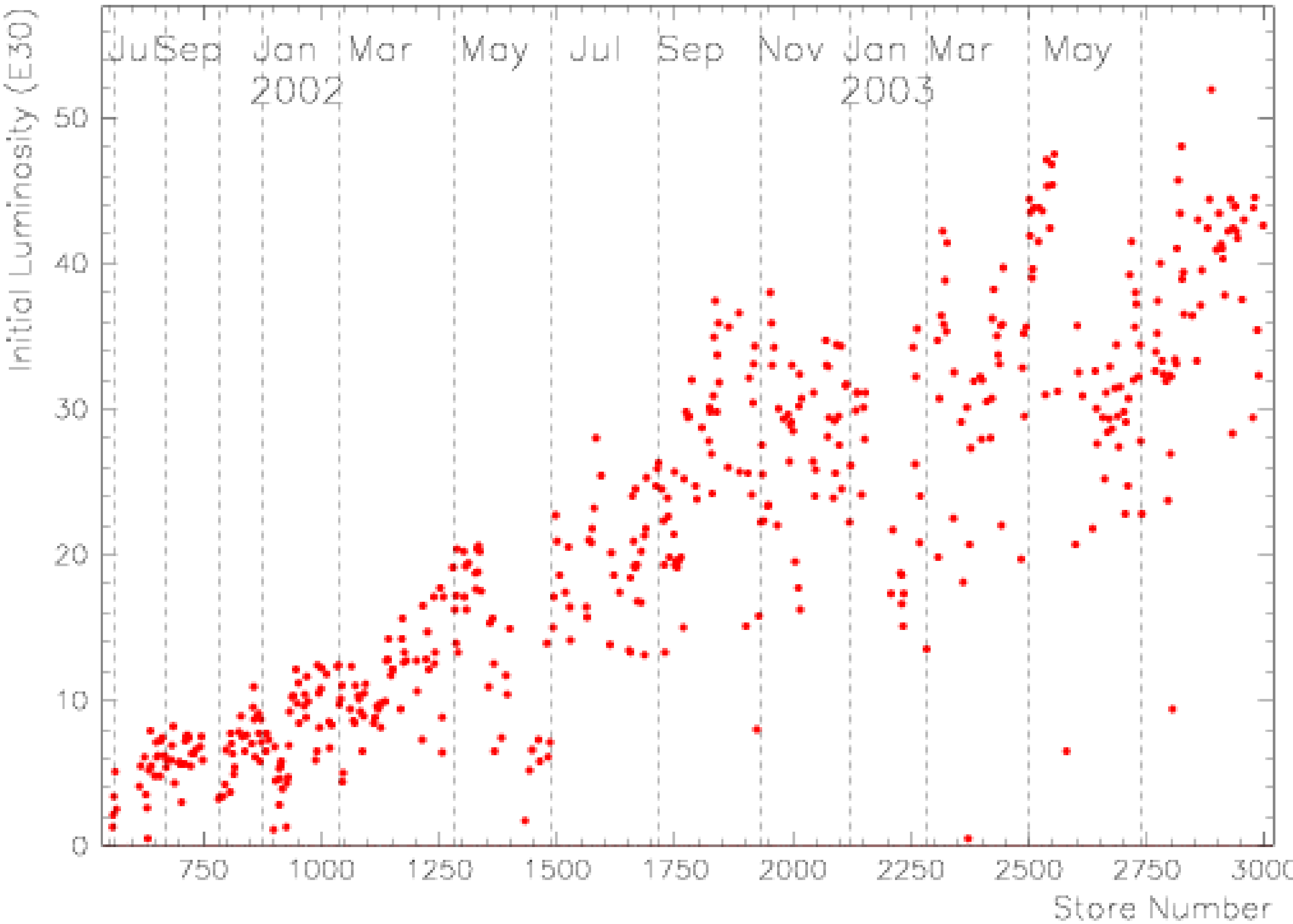
U.Baur, et al., Snowmass 2001, hep-ph/0111314

Statistical Error – Run I vs Run II





Initial Luminosity



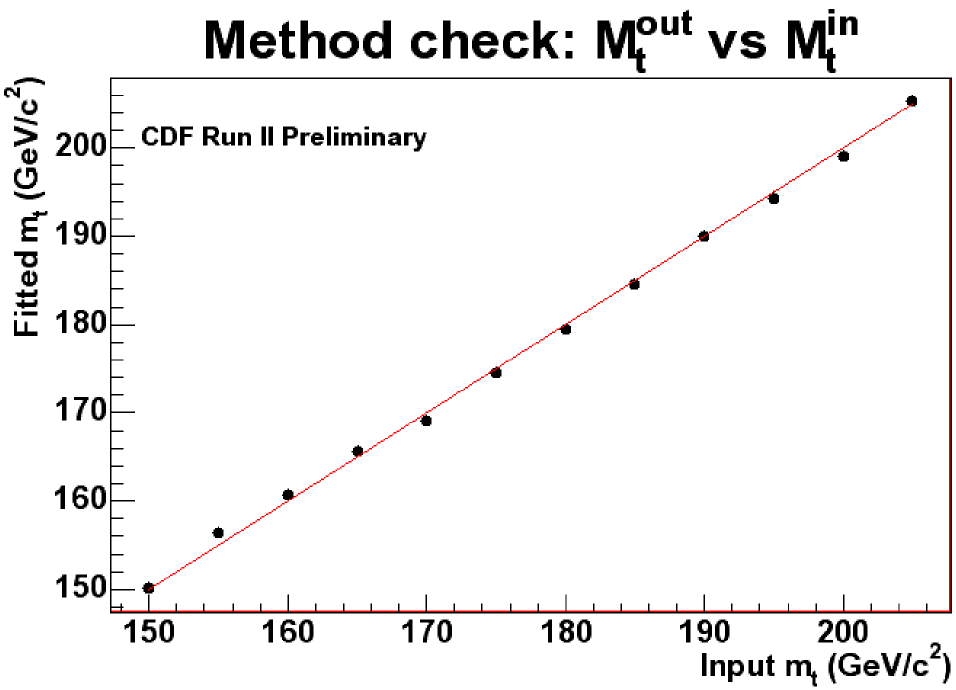
Record init lumi
5.2 E 31

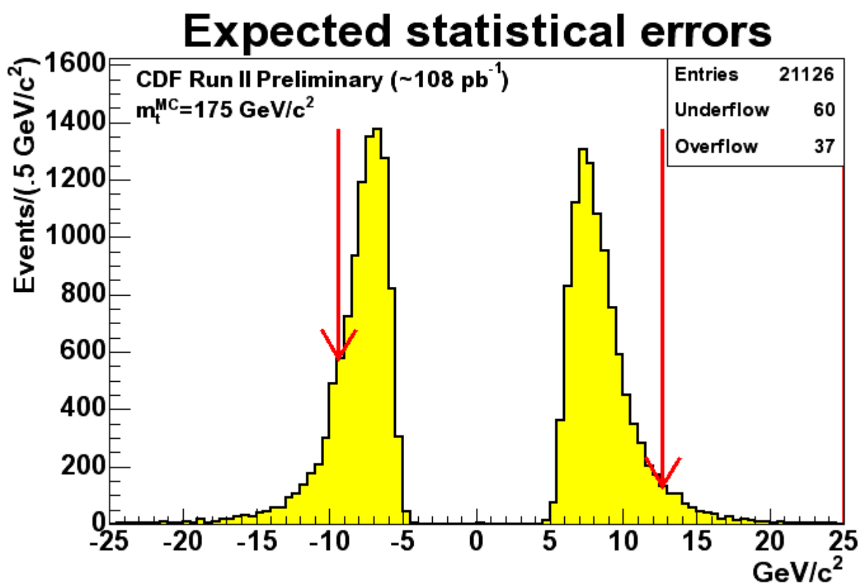
Detailed Event Selection

	Variable	Value
Global Event	Z and cosmic veto	applied
	$\not{E}_t$	> 20 GeV
	# of tight leptons	$= 1$
Jets	E_T of the three highest energy jets	> 15 GeV
	E_T of the 4^{th} jet	> 8 GeV
	$\lvert\eta^{detector}\rvert$	< 2
Electrons	Region	CEM in the fiducial region
	E_T	> 20 GeV
	p_T	> 10 GeV/c
	E/p (if $p_T < 50$ GeV/c)	< 2.0
	E_{had}/E_{EM}	$< 0.055 + 0.00045 \cdot E$
	L_{shr}	< 0.2
	$\lvert\Delta z\rvert$ (track to CES match in z)	< 3 cm
	$Q \times \Delta x$ (track to CES match in $r-\phi$)	between -1.5 and $+3.0$ cm
	χ^2_{strip}	< 10
	$\lvert z_0\rvert$ of COT track	< 60 cm
	# of COT axial SL segments	> 3
	# of COT stereo SL segments	> 3
	Calor. isolation ratio in cone of 0.4	< 0.1
	Not a conversion	
Muons	Region	CMUP or CMX
	p_T	> 20 GeV/c
	E_{EM}	$\max(2,\ 2 + 0.0115 \cdot (p - 100))$
	E_{had}	$\max(6,\ 6 + 0.0280 \cdot (p - 100))$
	$\lvert\Delta x\rvert_{\texttt{CMU}}$	< 3 cm
	$\lvert\Delta x\rvert_{\texttt{CMP}}$	< 5 cm
	$\lvert\Delta x\rvert_{\texttt{CMX}}$	< 6 cm
	$\lvert z_0\rvert$ of COT track	< 60 cm
	$\lvert d_0\rvert$ if no Si hits	< 0.2 cm
	$\lvert d_0\rvert$ if Si hits	< 0.02 cm
	# of COT axial SL segments	> 3
	# of COT stereo SL segments	> 3
	COT exit radius (CMX only)	> 140 cm
	Calor. isolation ratio in cone of 0.4	< 0.1

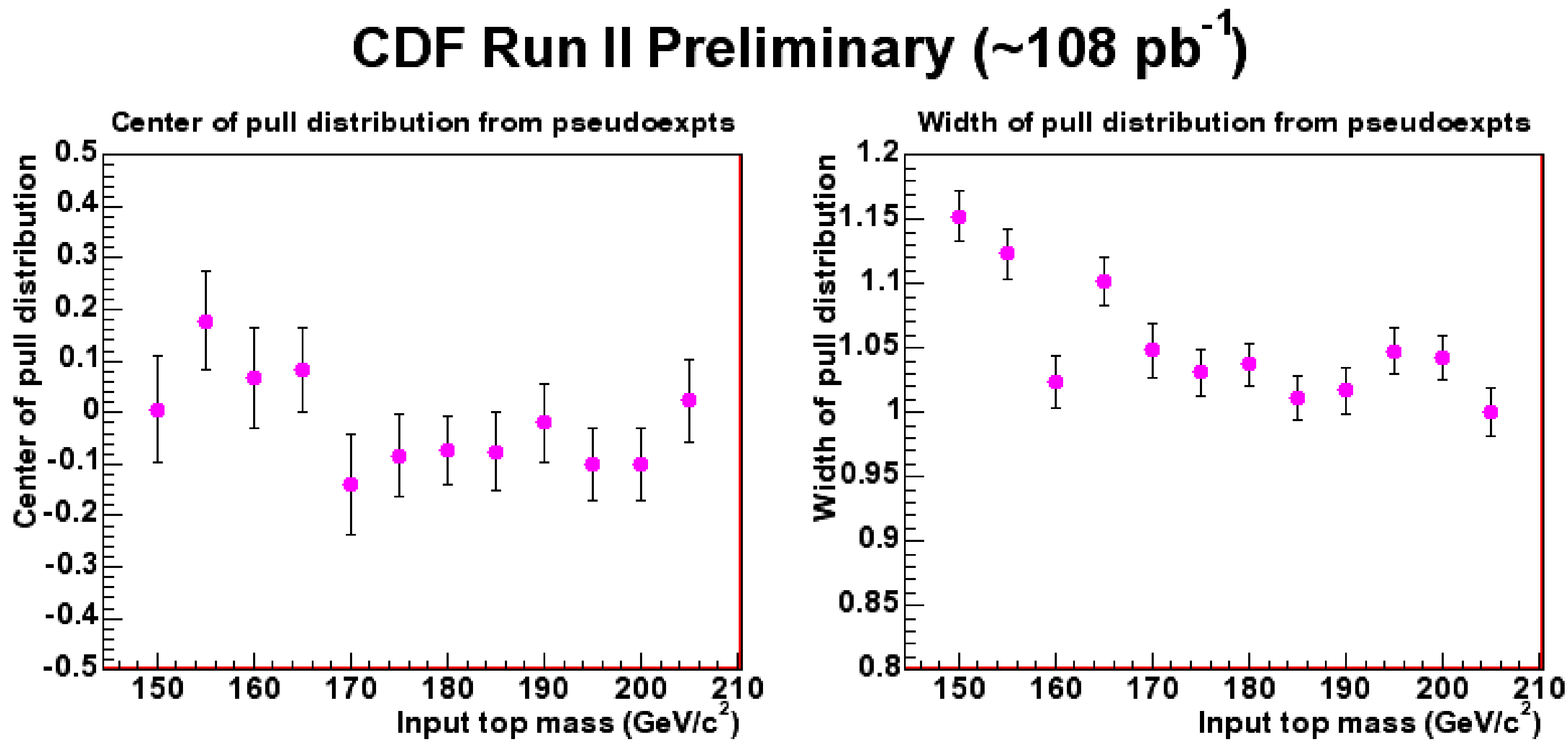
Pseudo-experiments

- Take a large number (e.g. 10,000) of samples of x events, drawn from signal and background MC.
- Run through the full machinery.
- Consistency checks, and evaluation of systematics

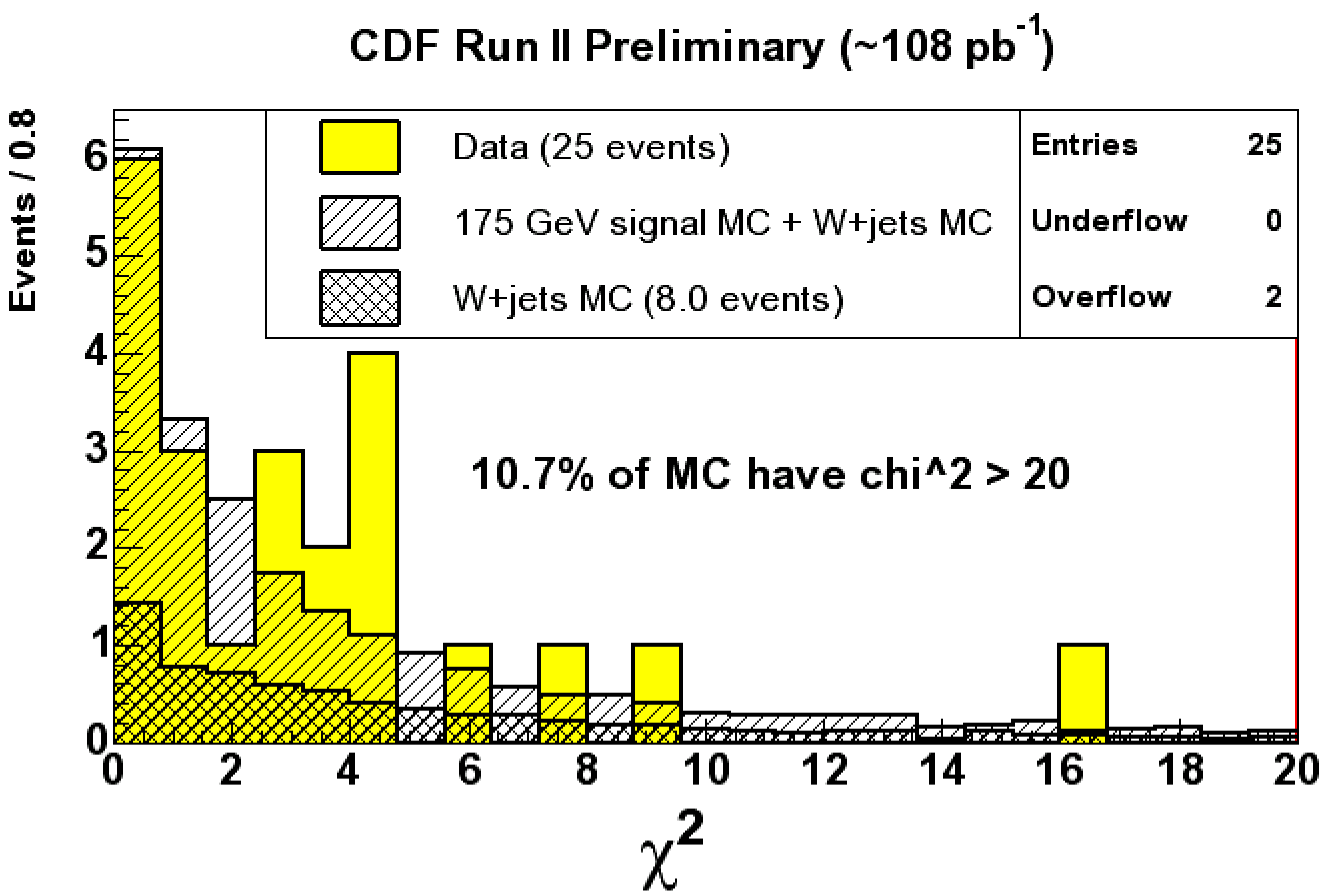




Pull distributions



Chi^2 cut



CDF Run II Preliminary (~108 pb^{-1})
Events / 0.8
Data (25 events)
175 GeV signal MC + W+jets MC
W+jets MC (8.0 events)
Entries 25
Underflow 0
Overflow 2
10.7% of MC have chi^2 > 20
0 1 2 3 4 5 6
0 2 4 6 8 10 12 14 16 18 20
χ^2

Detailed Jet Systematics

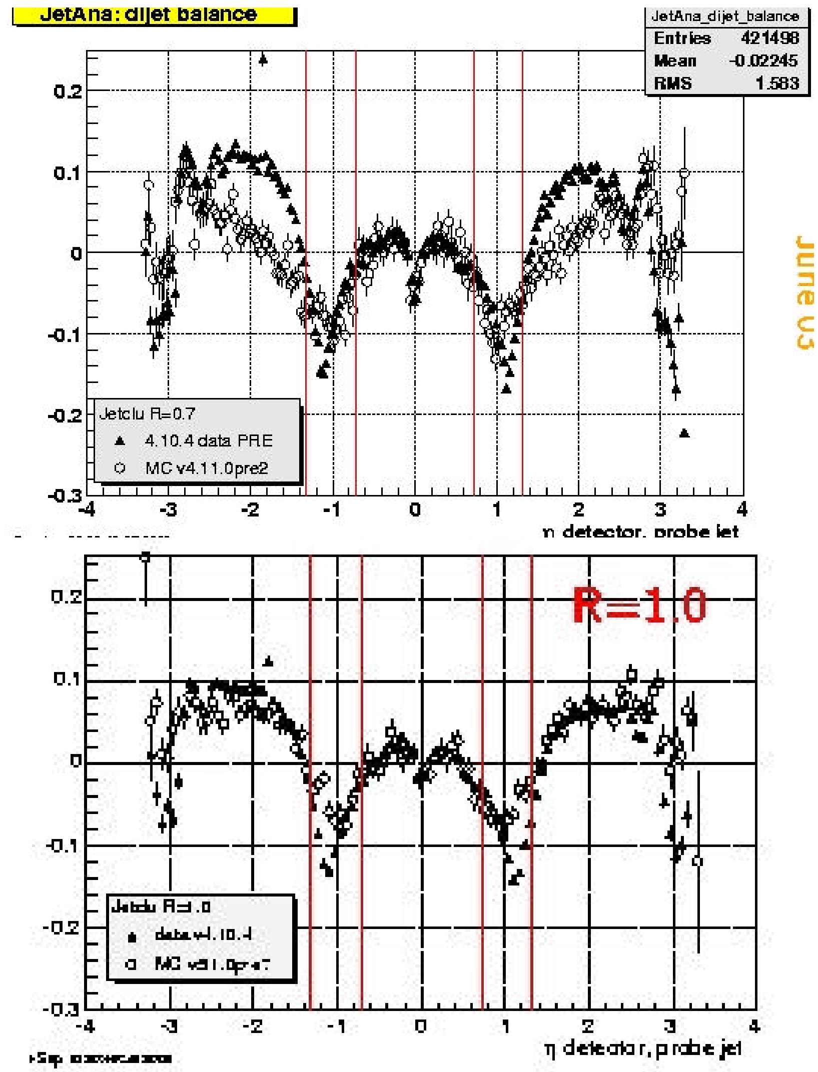
Source of Corrections		ΔM_{top} (GeV/c^2)		
Level	Description	`v4.9.1hpt1`	`v4.11.1 REMAKE`	
		$\geq$ 3.5 jets	$\geq$ 3.5 jets	$\geq$ 4 jets
1 (sim)	η-Dependent Calibration **	3.77 ± 0.24	2.42 ± 0.06	2.40 ± 0.07
1 (data)	η-Dependent Calibration **	0.91 ± 0.24	1.60 ± 0.07	1.79 ± 0.07
2 (data)	Calorimeter Stability	0.99 ± 0.24	0.98 ± 0.07	0.87 ± 0.07
3 (sim)	Raw Scale (central) **	4.45 ± 0.24	3.51 ± 0.07	3.89 ± 0.07
3 (data)	Raw Scale (central) **	4.87 ± 0.24	2.71 ± 0.07	2.86 ± 0.07
5	Absolute Scale	2.17 ± 0.24	2.44 ± 0.07	2.42 ± 0.07
7	Out-of-Cone: up to cone 1.0	1.21 ± 0.24	1.33 ± 0.07	1.43 ± 0.07
	Out-of-Cone: outside cone 1.0	1.15 ± 0.24	1.24 ± 0.07	1.52 ± 0.07
Total		7.9 ± 0.7	6.2 ± 0.2	6.6 ± 0.2

h-Dependent Corrections, Di-Jet Balancing

- To account for cracks (gaps, or less sensitive regions) in the calorimeter
- Trigger Jet, Probe Jet

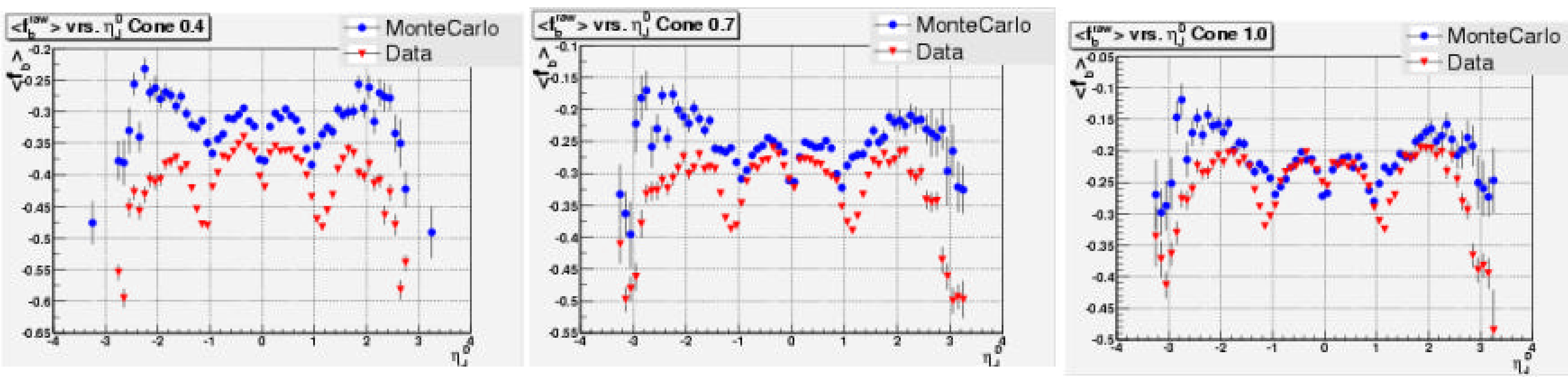
$$B = (P_t^{probe} - P_t^{probe}) / 0.5\ (P_t^{probe} + P_t^{probe})$$

- Corrected low energy pion response in calorimeter MC



Raw Scale, g-Jet Balancing

- γ-Jet Balancing primary check of jet scale
- Run I – Run II Differences partially understood
- Data-MC differences still extant



cone	Run 1 fb	Run 2 fb	Run2-Run1 KJ
0.4	-32.1±0.3	-36.2±0.1	1.065±0.005
0.7	-24.8±0.2	-28.7±0.1	1.055±0.004
1.0	-18.9±0.2	-23.3±0.1	1.058±0.003

fb=Pt(jet)/Pt(ã)-1

$$KJ= \frac{fb(run1)+1}{fb(run2)+1}$$

From Fermilab W&C, 4/21/03, J. Estrada

Lepton+jets channel

DØ Statistics Run I : 125 pb^{-1}

Standard Selections :

- Lepton: E_t>20 GeV,$|\eta^e|<2$,$|\eta^\mu|<1.7$
- Jets: ≥4, E_T>15 GeV, $|\eta|<2$
- Missing E_T> 20 GeV
- "E_T^W"> 60 GeV ; $|\eta_W|<2$

→ **91 events**

Ref. PRD 58 (1998), 052001:

After χ^2(77 events): ~29 signal + ~48 backg.

(0.8 W+*jets* and 0.2 QCD)

Specific cuts for this analysis:

- **4 Jets only :** → **71 events**
- **Background Prob. :** → **22 events**

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From Fermilab W&C, 4/21/03, J. Estrada

Acceptance Corrections

Likelihood

$$-\ln L(\alpha) = -\sum_{i=1}^{N} \ln P(x_i;\alpha) + N\int P(x;\alpha)dx$$

Detector Acceptance

$$P(x;\alpha) = Acc(x)P_0(x;\alpha)$$

Measured probability

Detector acceptance

Production probability

$$-\ln L(\alpha) = -\sum_{i=1}^{N} \ln P_0(x_i;\alpha) + N\int Acc(x)P_0(x;\alpha)dx$$

$$\int Acc(x)P_0(x;\alpha)dx = \frac{12V}{N_{gen}} \sum_{j=accep.}^{N} P_0(x_j;\alpha)$$

where $V = \int d^n\sigma_{MC}(y)dq_1dq_2 f_{MC}(q_1)f_{MC}(q_2)$, N_{gen}(N) is number of generated(observed) events

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$$-\ln L(\alpha) = N\int A(x)\left[c_1 P_{tt}(x;\alpha) + c_2 P_{bkg}(x)\right]dx$$

$$-\sum_{i=1}^{N}\left\{\ln\left[c_1 P_{tt}(x_i;\alpha) + c_2 P_{bkg}(x_i)\right]\right\}$$

Transfer Function (Estrada)

Transfer function W(x,y)

W(x,y) probability of measuring x when y was produced (x jet variables, y parton variables):

$$W(x,y)=\delta^3(p_e^y-p_e^x)\prod_{j=1}^{4}W_{jet}(E_j^y,E_j^x)\prod_{i=1}^{4}\delta^2(\Omega_i^y-\Omega_i^x)$$

where

E^y	energy of the produced quarks
E^x	measured and corrected jet energy
$p^y{}_e$	produced electron momenta
$p^x{}_e$	measured electron momenta
$\Omega^y{}_j, \Omega^x{}_j$	produced and measured jet angles

Energy of electrons is considered well measured, an extra integral is done for events with muons. Due to the excellent granularity of the DØ calorimeter, angles are also considered as well measured. A sum of two Gaussians is used for the jet transfer function (W_{jet}), parameters extracted from MC simulation.

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Probability (Estrada)

Probability for $t\bar{t}$ events ("$d\sigma$")

$$P_{t\bar{t}} = \frac{1}{\sigma_{tot}} \int d\rho_1 dm_1^2 dM_1^2 dm_2^2 dM_2^2 \sum_{comb,\nu} |M|^2 \frac{f(q_1)f(q_2)}{|q_1||q_2|} \phi_6 W_{jet}(x,y)$$

2(in) + 18(final) = 20 degrees of freedom

3(e) + 8(Ω1..Ω4) + 3(P_{in}=P_{final})+1(E_{in}=E_{final}) = 15 constraints

20 – 15 = 5 integrals

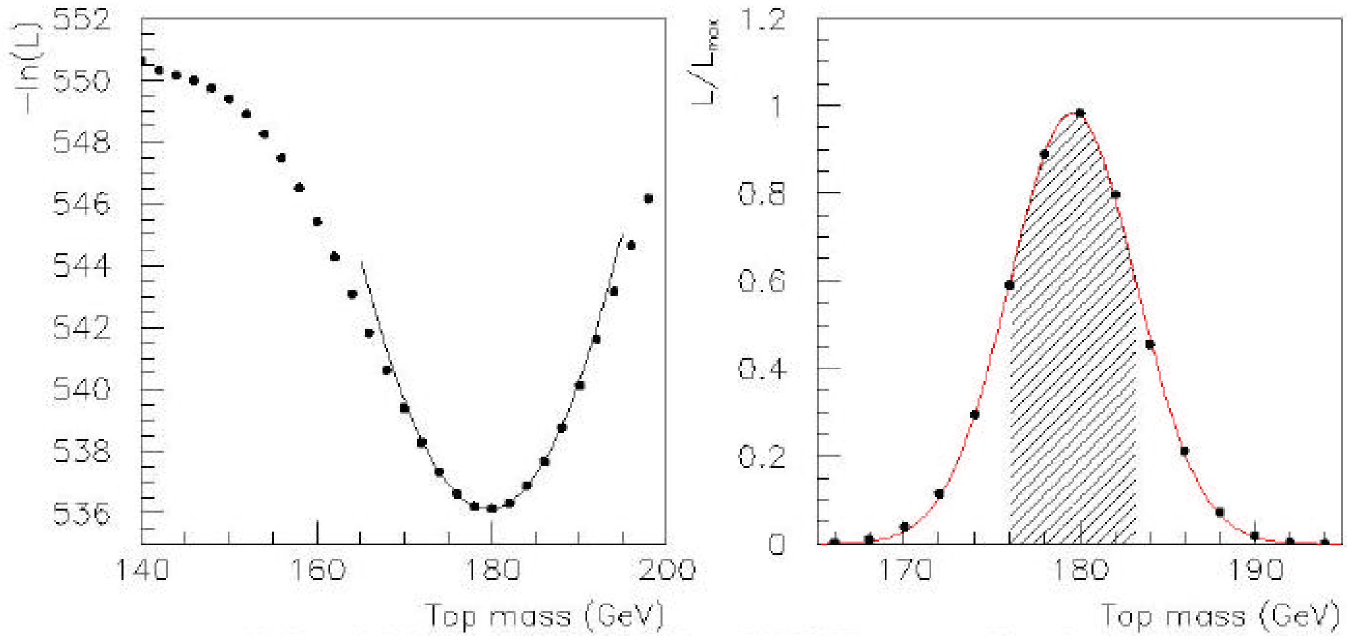
Sum over 24 combinations of jets, all values of the neutrino momentum are considered. Because it is L.O., we use only 4-jet events.

ρ_1	momentum of one of the jets	m_1, m_2	top mass in the event
M_1, M_2	W mass in the event	$f(q_1), f(q_2)$	parton distribution functions (CTEQ4) for qq incident chann.
q_1, q_2	initial parton momenta	ϕ_6	six particle phase space
$W(x,y)$	probability of measuring x when y was produced in the collision		

We choose these variables of integration because $|M|^2$ is almost negligible, except near the four peaks of the Breit-Wigners within $|M|^2$.

D0 results from data

New Preliminary Result



M_t = 180.1 ± 3.6 GeV ± SYST - preliminary

This new technique improves the statistical error on M_t from 5.6 GeV [PRD 58 52001, (1998)] to 3.6 GeV. <u>This is equivalent to a factor of 2.4 in the number of events.</u> 22 events pass our cuts, from fit: (12 s + 10 b)

(0.5 GeV shift has been applied, from MC studies)

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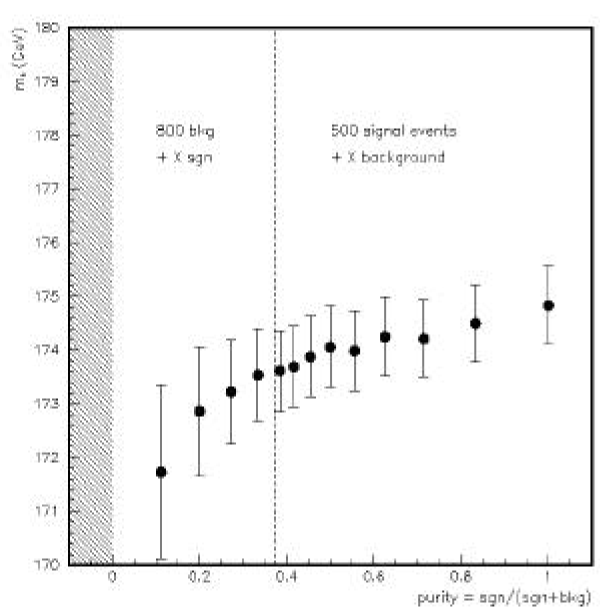
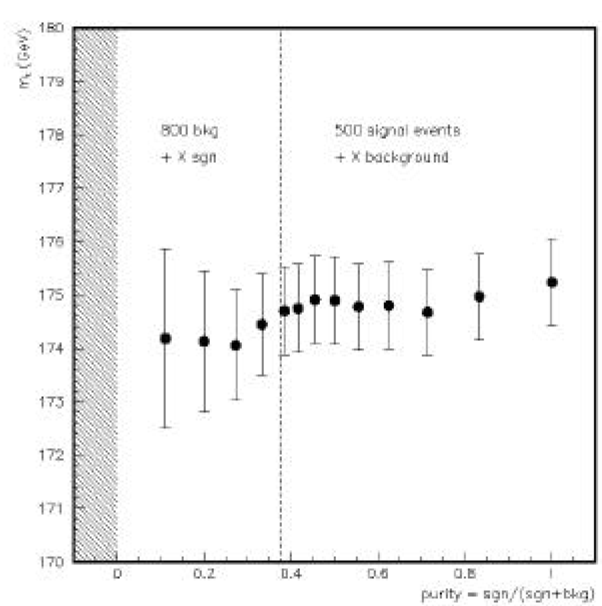
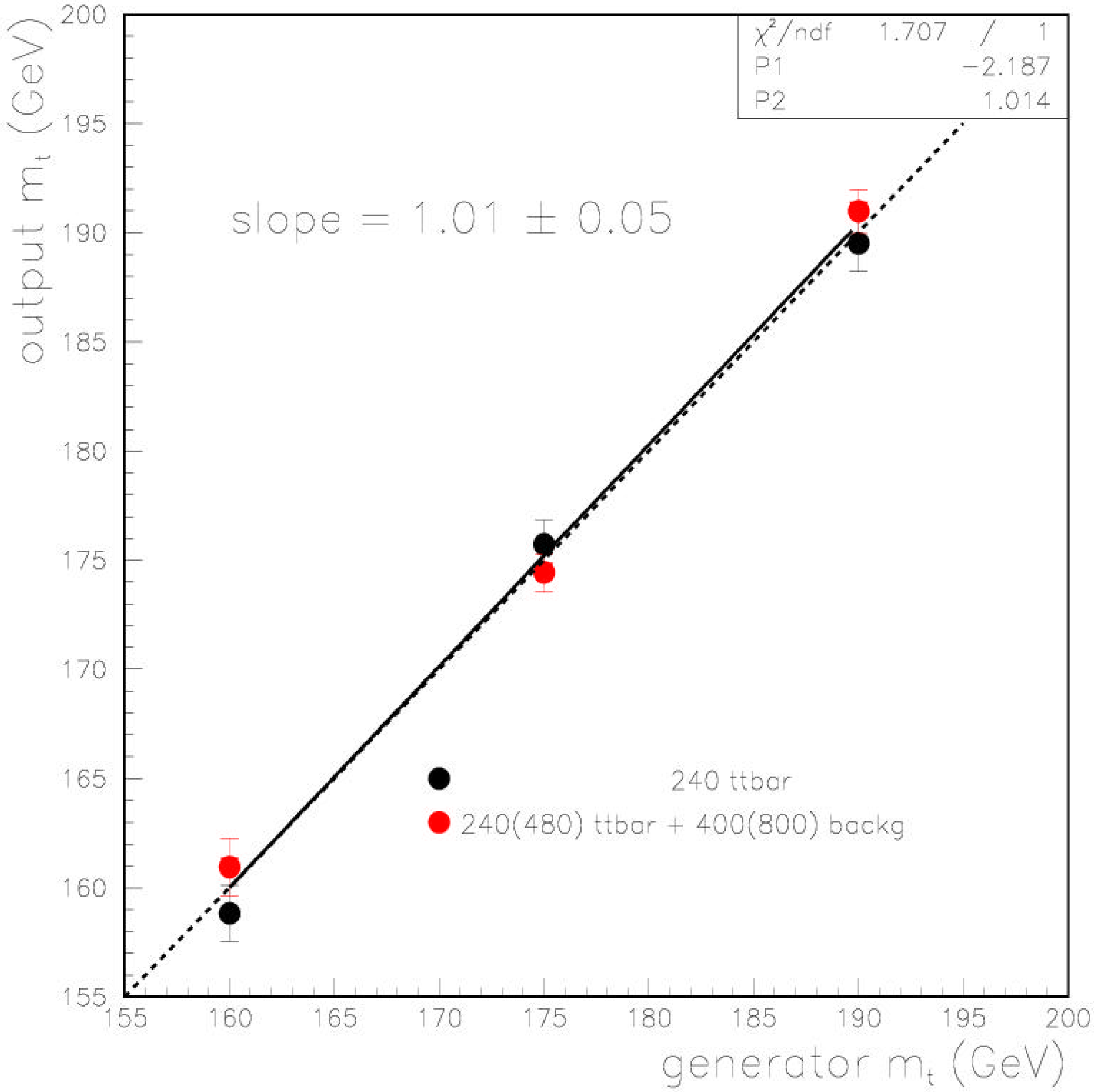
Bias due to background fraction

- D0 saw, in MC, a bias as a function of background fraction
- Applied a cut on background probability
  - Eliminated 70% of W+jets and 77% of QCD background
  - Eliminated 30% of ttbar events.
- 22 events in data, 12 ± 4 background





D0 check for bias of method

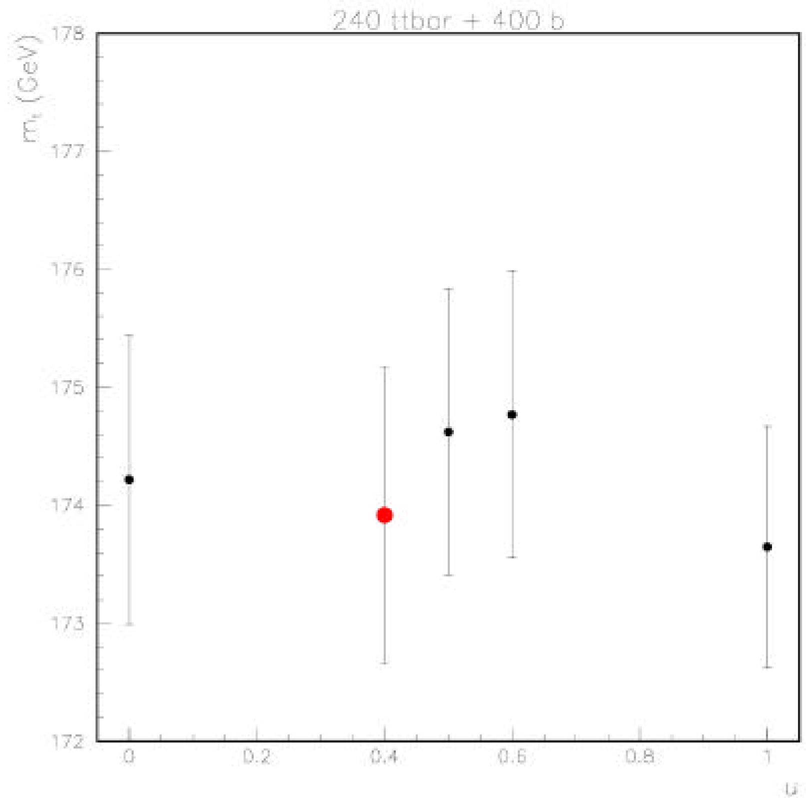


1.014 ±0.05?

How big of a correction would this make?

Signal model systematic

- Vary u, the fraction of events in MC where you cannot (can?) match all 4 jets to partons.
- 1.5 GeV systematic error.



D0 (2003)

Extracting the transfer functions

- We have separate transfer functions for light quark and b quark jets.
- We use two gaussians, hoping that one gaussian will take the peak and the other (stretched out) gaussian the asymmetric tails. May be able to find a better parameterization.

$$d_E = E_{parton} - E_{jet}$$

$$F(d_E) = \frac{1}{\sqrt{2p}\,(p_2 + p_3 p_5)}\left[\exp\frac{-(d_E - p_1)^2}{2p_2^2} + p_3 \exp\frac{-(d_E - p_4)^2}{2p_5^2}\right]$$

•$W(E_{parton}, E_{jet}) = F(d_E)$

•Parameters depend linearly on parton energy: $p_i = a_i + b_i E_{parton}$

•Normalized so that, for a given E_{parton}, W is the probability density function for getting a given E_{jet}.

$$\int_0^\infty W(E_{parton}, E_{Jet})\, dE_{Jet} = 1$$

•10 total parameters, extracted from an unbinned likelihood fit of ordered (E_{parton}, E_{jet}) pairs.

Possible sources of systematic bias

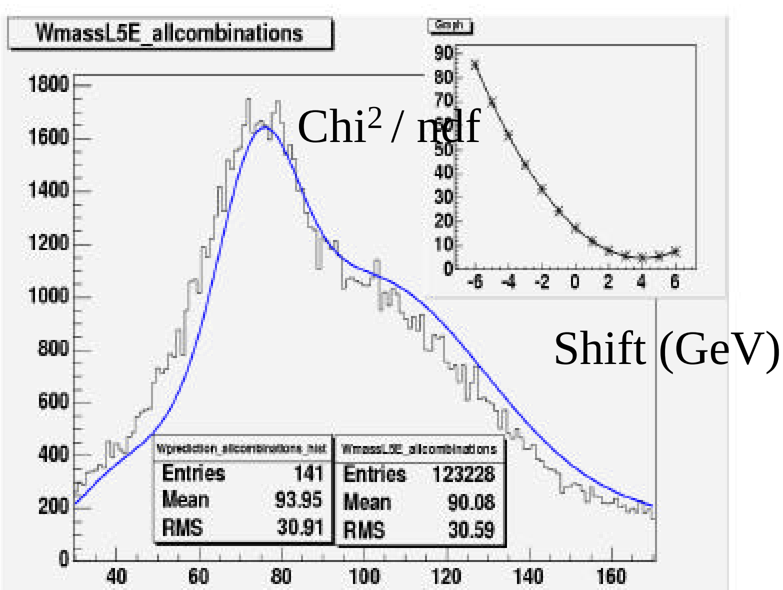
- Possible that the fits of the transfer function parameterization to the reconstructed MC are just bad.
  - Difficult to consider goodness of fit globally.
  - Could take slices in E_{parton} and compare fit to MC.
- The two jets from W decay are correlated
  - Transfer functions treat them as independent.
  - Given E_{parton}, when Δr is small transfer functions will overestimate E_{jet}.
    When Δr is large transfer functions will underestimate.
- We have a hard cutoff at E_{jet} = 15 GeV, parameterization doesn't take this into account.
  - May be able to change normalization to account for this. $\int_{15}^{\infty} W(E_{parton}, E_{Jet})\, dE_{Jet} = 1$

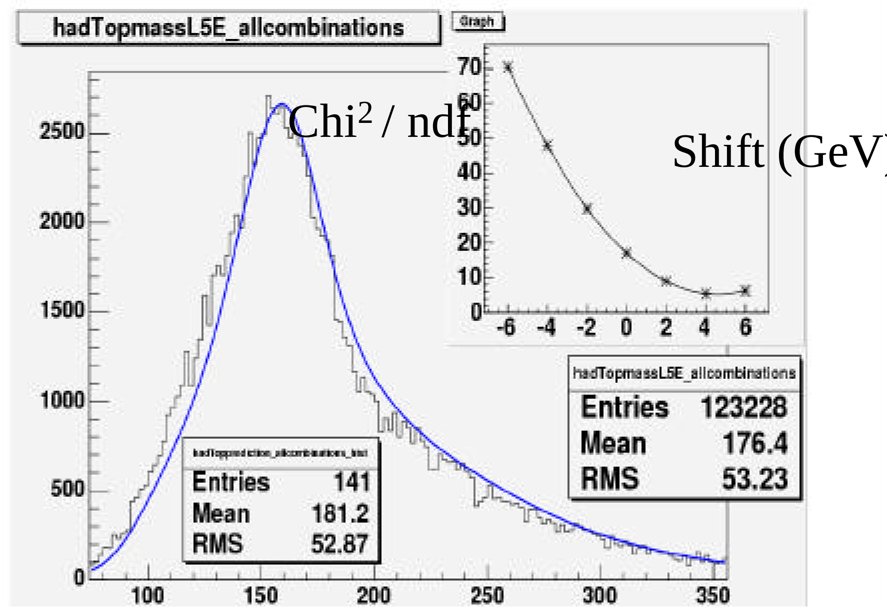
•When taking integrals for mass, we're under weighting events with low parton energies – they already passed event selection at jet level.

•May be able to reweight them.

•Or, can start with a more inclusive sample, where the deweighting would be appropriate.

Hadronic W and top mass from transfer functions – 12 combinations





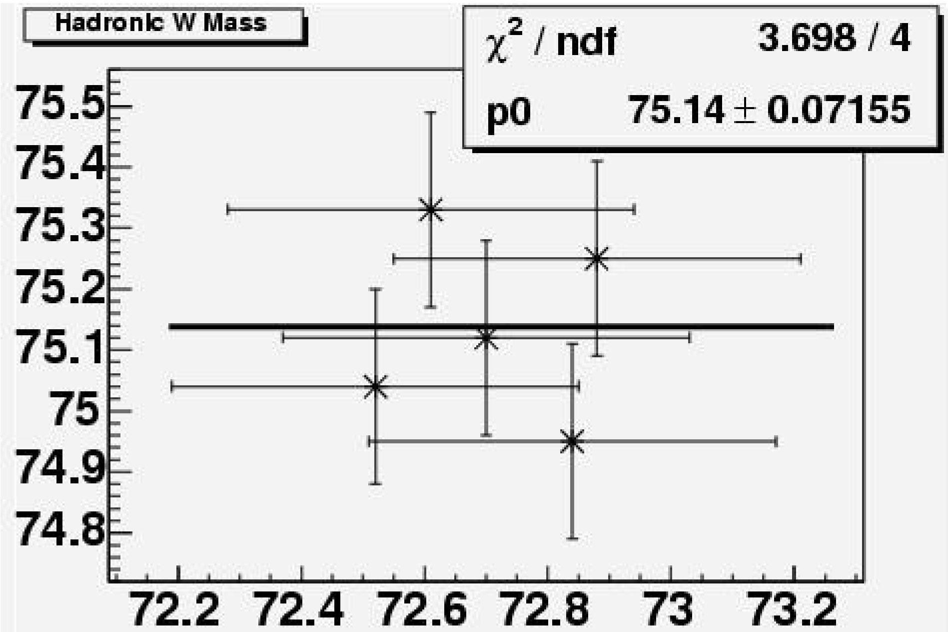
Hadronic W mass (GeV) Hadronic top mass (GeV)

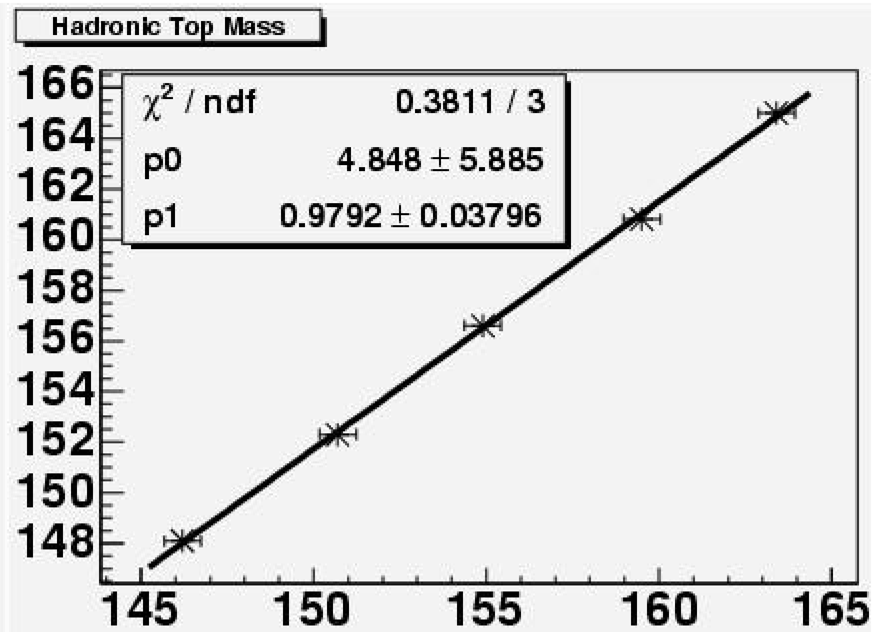
- •Histogram from simulated, reconstructed Herwig jets.
- •Blue curve is prediction from transfer function, using parton level Herwig.
- •Inset is chi^2 as we shift the histogram against the prediction.
- •**Note that the prediction is systematically high!**

Test of mass dependence of transfer functions

•Extract transfer functions from 175 GeV Herwig ttbar MC

•Apply them to 165,170,175,180,185 GeV Herwig, compare prediction to simulation





Predicted hadronic W mass vs. simulated, reconstructed W mass (GeV)

Predicted hadronic top mass vs. simulated, reconstructed top mass (GeV)

Systematics

D0 (1998)

TABLE XXIX. Systematic uncertainty summary.

	LB (GeV/c^2)	NN (GeV/c^2)	Average (GeV/c^2)
Jet energy scale	4.2	3.8	4.0
Generator			
$t\bar{t}$ signal	1.9	1.9	1.9
VECBOS flavors	2.5	2.5	2.5
Noise/MI	1.3	1.3	1.3
Monte Carlo stat.	0.6	1.1	0.85
LB/NN diff	0.8	0.8	0.8
Likelihood fit	1.0	1.0	1.0
Total	5.6	5.4	5.5

Phys. Rev. D {58} 052001 (1998)

D0 (2003)

Systematic Uncertainties for top quark mass

Determined from MC studies with large event samples:

Signal model	1.5 GeV/c^2
Background model	1.0 GeV/c^2
Noise and multiple interactions **PRD 58 52001, (1998)**	1.3 GeV/c^2

Determined from data:

Jet Energy Scale	3.3 GeV/c^2
Parton Distribution Function	0.2 GeV/c^2
Acceptance Correction	0.5 GeV/c^2

Run I CDF syst

Source	Uncertainty (GeV/c^2)
Jet energy measurement	4.4
Initial and final state radiation	2.6
Shape of background spectrum	1.3
b-tagging	0.4
Parton distribution functions	0.3
Monte Carlo generators	0.1
Total	5.3

Source of Syst.	ΔM_{top} (GeV/c^2)
Jet Energy	6.2
ISR	1.3
FSR	2.2
Generators	0.5
PDFs	2
Other MC modeling (Jet Resolution, p_T^{top})	1
Background Shape	0.5
b-tagging	0.1 (Run I)
Total	7.1